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FOREST BLOWDOWN FROM NUCLEAR AIRBLAST

Phillip J. Morris

URS Research Company

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by

Phillip J. Morris

for

Headquarters
DEFENSE NUCLEAR AGENCY
Washington, D.C. 20305

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A sensitivity analysis is performed on a computer model of tree response to airblast loading. This effort was undertaken, with success, to reduce the number of input parameters required by the model to those available to the field commander. Based on the results of this analysis, a new prediction technique was developed which determines the extent of tree blowdown and the resultant effects on troop and vehicle movement. The technique was developed for inclusion in DNA Effects Manual Number 1.

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Section I
INTRODUCTION

The effects of airblast from nuclear detonations on forests have periodically been the subject of research over the last twenty years. The interest in this subject stems from the recognition that such effects can have an impact on military operations. Forests have been traditionally used for cover and concealment of military forces as well as impediments to certain types of military movement. Thus, a change in the condition of a forest caused by a nuclear detonation can have significant impacts on tactical military operations. It is of importance, therefore, to be able to adequately predict forest blowdown.

Section II

OBJECTIVES AND REPORT ORGANIZATION

The basic objective of this research is to incorporate the current state of the art into a prediction technique that will be militarily useful in determining forest damage from airblast. This objective was accomplished in two stages. The first stage updated the iso-damage height-of-burst charts presently contained in EM-1. The second stage included a detailed examination of the computer model used for predicting blowdown (described in Ref. 1), and adaptation into a simplified prediction technique.

The specific contract objectives are to:

1. Perform the necessary data analysis, curve fitting, and computer code modifications required to enable the forest blowdown computer code documented in DASA 2300 to calculate blowdown for foliated and defoliated broadleaf forests.

2. Perform an immediate update of the forest-damage, height-of-burst curves for the eight forest types presently used in DASA EM-1 using the U.S. Forest Service Tree Blowdown Model.

3. Perform a sensitivity analysis of the input parameters for the U.S. Forest Service Tree Blowdown Model with a view toward preparing a simplication of the model that does not entail an unacceptable loss in accuracy.

Objectives 1 and 2 have been accomplished and are reported in Refs. 2, 3, and 4. The research and results accomplished for Objective 3 are reported herein.

The remainder of this report is organized as follows. Section III contains background information and summary results of previous investigations. Section IV contains the results of work accomplished on the third objective — a sensitivity analysis of the input parameters for the U.S. Forest Service Tree Blowdown Model. Section V covers the assumptions and approach used to develop the updated blowdown prediction technique. Mathematical relationships used in the sensitivity analysis are included as Appendix A.

Section III
BACKGROUND AND PREVIOUS INVESTIGATION

The first efforts to develop a mathematical model for the response of trees to transient airblast drag loading were performed in 1951 (see Ref. 5). Research continued and culminated in the first prediction technique which is reported in Ref. 6. This reference also presents the mathematical model which had been developed to support the prediction technique. Subsequent research refined the model and verified its predictions for a number of high-explosive tests (see Ref. 3). At the conclusion of this research, a verified computer model was available. However, its use was cumbersome because the large number of input variables and the numerous mathematical relationships required computerization. This was circumvented to some extent by the development of prediction techniques for several forest types for which calculations had been performed. This approach imposed limitations on flexibility and accuracy as the forest of interest may not match one of the forest types for which calculations were available. It was recognized that the more desirable solution was to selectively simplify the computer model, based on an analysis of the sensitivity of results to variations in input parameters, so that predictions of acceptable accuracy could be made based on information obtainable from military reconnaissance.

Section IV
SENSITIVITY ANALYSIS

Synopsis of Tree Blowdown Model

A brief description of the tree blowdown model which has been excerpted from Ref. 1 is presented here to identify the necessary input parameters and as a guide to the calculational procedures used.

The tree blowdown model is based on a series of calculations on the response of trees to airblast loading. For the purposes of calculation, the tree stem and crown were portrayed as a one-degree-of-freedom spring and mass system, with the mass located at the experimentally determined aerodynamic center-of-pressure of the tree crown. The spring, representing the tree stem, was assumed to undergo elastic, perfectly plastic deformation.

For a series of characteristic trees having properties of Ponderosa pine, maximum response was calculated by time-wise integration of the equation of motion for a series of variations of airblast overpressures and weapon yields. Even though the tree response was nonlinear, e.g., the crown drag coefficient varied with magnitude of crown deformation, the results of these calculations can be correlated as a three-parameter family of curves relating the maximum energy absorbed by the spring to the strength and duration of the airblast and to the natural period and drag characteristics of the tree crown. Figure 1 shows this relationship where*

$$\bar{E}_1 = \frac{\text{Energy absorbed by spring at maximum deflection}}{\text{2 times the energy absorbed by linear spring at deflection corresponding to modulus of rupture of green wood}}$$

τ = Tree natural period of vibration (with crown intact)

t_+ = Positive phase duration of airblast

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* In the text we adopt the nomenclature of Ref. 6 (see Table I). The computer program BLOWDOWN uses a phonetically similar set of symbols. The correspondence is given in Table I.

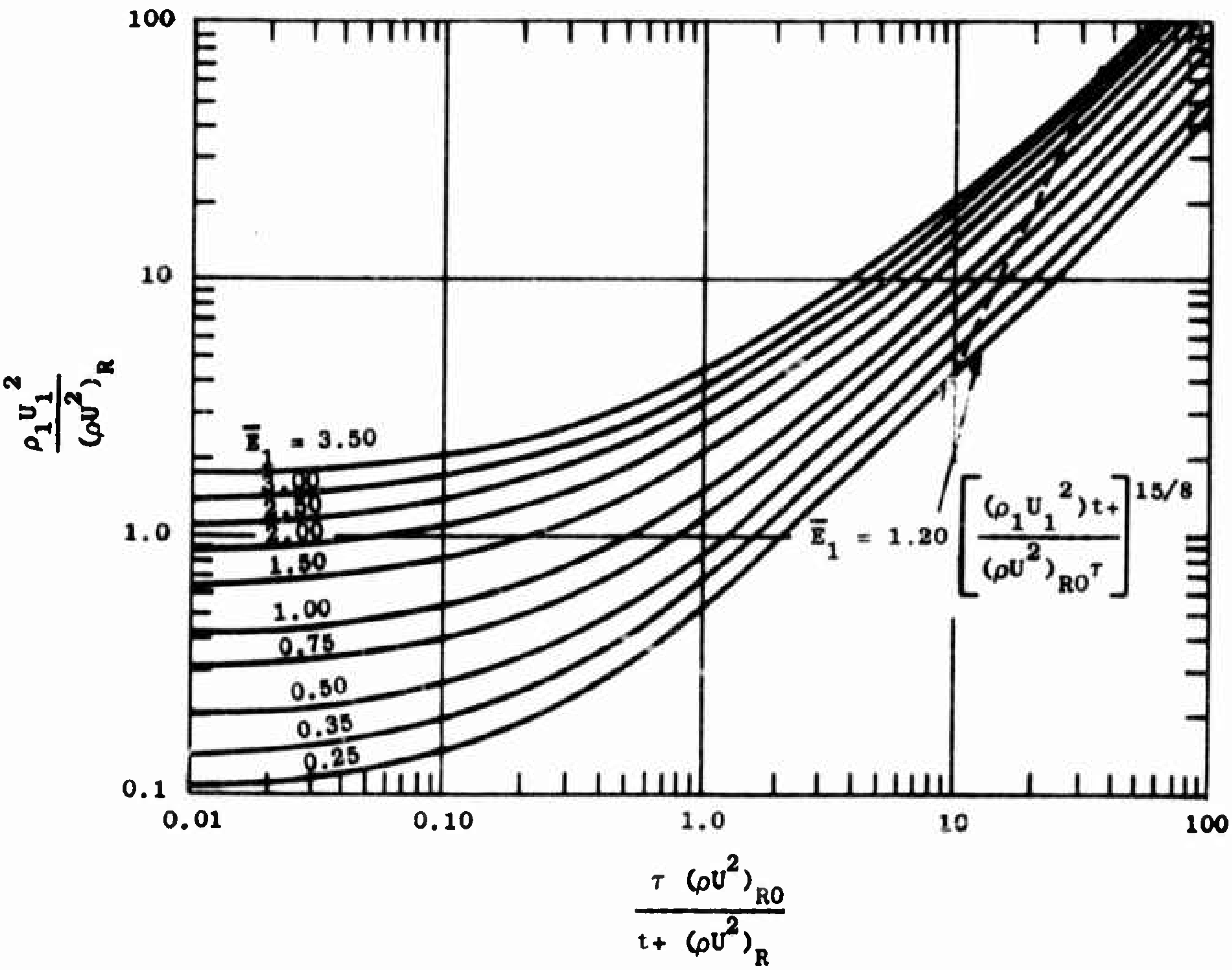

Fig. 1. Tree Response as a Function of Airblast Dynamic Pressure and Positive Duration

Table I

NOMENCLATURE

Text		Blowdown
a	= stem form factor	A
c	= stem form factor	B
d	= diameter along stem inside bark, in.	
d_{bh}	= stem diameter (outside bark) at breast height, in.	DBH
d_c	= diameter of stem at base of crown inside bark, in.	DC
d_i	= stem diameter inside bark at breast height, in.	DI
D	= measured horizontal drag force of tree crowns, lbs	
$\bar{E}_b$	= deflection energy modulus for breakage	EB
$\bar{E}_1$	= deflection energy modulus for first maximum deflection	
f	= H/H_{bh}, of stem downward fractional height of stem measured from top	
f_1	= $\bar{H}_{cp}/H_{bh}$, fractional position of loading	FP
f_c	= H_c/H_{bh}, fractional position of base of crown	FC
f_m	= H_m/H_{bh}, fractional position of maximum stress	FM
h	= distance from base of crown to center of pressure, ft	
H	= height of stem measured from top of stem downward, ft	
H_{bh}	= height of stem above breast height, ft	HBH
H_c	= length of crown, ft	HC

Table I Continued

$\bar{H}_{cp}$	= H_c-h, distance to center of pressure, ft	HP
I_+	= dynamic pressure impulse, lbs sec/in.^{2}	IQ
k_r	= theoretical spring constant, lbs/ft	
L_t	= total length of stems broken per acre in all tree diameter classes, ft/acre	LT
N_n	= number of trees per acre in a diameter class	N
Δp	= peak overpressure, lbs/in.^{2}	P
P_1	= probability of stem breakage on first deflection	PB
P_t	= total probability of stem breakage	PBT
	= dynamic pressure waveform factor	
R	= horizontal applied force, or restoring force, lbs	
R_r	= reference horizontal applied force, lbs	
S_m/S_{bh}	= maximum extreme fiber stress/extreme fiber stress at breast height	SMB
S_r	= modulus of rupture of green wood, lbs/in.^{2}	SR
t_+	= positive phase duration time of shock, sec	
w	= detonation yield, tons	Z
w	= bomb yield, kt	Z
W_b/W_f	= weight of dry branchwood/weight of dry foliage	WBF
W_c	= weight of dry crown, lbs	WC

Table 1 Continued

W_o	= weight of dry crown, dry branchwood, or dry foliage, (as the case may be), lbs	
y	= stem deflection at loading point, ft	
$\frac{\rho_1 U_1^2}{2}$	= peak dynamic pressure in airblast, lbs/in.^{2}	Q
$\frac{(\rho U^2)}{2}_R$	= the dynamic pressure defined by Equation 3, lbs/in.^{2}	QR
$\frac{(\rho U^2)}{2}_{RO}$	= the dynamic pressure defined by Equation 2, lbs/in.^{2}	QRO
τ	= natural period of tree with crown, sec	T
ψ	= function	

From Fig. 1:

$\frac{\rho_1 U_1^2}{2}$ = The peak dynamic pressure of the airblast

$(\frac{\rho U^2}{2})R$ = The steady wind dynamic pressure corresponding to a tree stem stress equal to the modulus of rupture

$(\frac{\rho U^2}{2})RO$ = The impulsive dynamic pressure corresponding to a tree stem stress equal to the modulus of rupture

The last two parameters take into account the nonlinear response of the tree crown. When a tree is subjected to a gradually increasing wind, its branches deform in such a way that the aerodynamic drag of the tree crown is minimized. Wind tunnel tests of saplings and aerodynamic studies of full-sized tree crowns were the basis for the conclusion drawn that a more proper denominator than the projected crown area for the aerodynamic drag coefficient was the weight of a dry crown and that the drag coefficient so defined decreased as the strain at the base of the crown increased. This relationship is given in Ref. 6 as*

$$\frac{Dh}{d_c^3} \cdot \frac{W_b}{W_f} \div \frac{\rho U^2}{2} = \Psi(\frac{D}{W_c}) \tag{1}$$

so that

$$(\frac{\rho U^2}{2})RO = \frac{1}{\Psi(o)} \cdot \frac{R_r(H_c - \bar{H}_{cp})}{d_c^3} \cdot \frac{W_b}{W_f} \tag{2}$$

---

* Note: Eq. (1) is for conifer trees. The equation for broadleaf trees is:

$$\Psi\left(\frac{D}{W_c}\right) = \frac{Dh}{d_c^3} \div \rho\frac{U^2}{2}$$

The remaining equations would be modified accordingly.

$$\left(\frac{\rho U^2}{2}\right)R = \frac{1}{\Psi\left(\frac{R_r}{W_c}\right)} \cdot \frac{R_r(H_c-\bar{H}_{cp})}{d_c^3} \cdot \frac{W_b}{W_f} \tag{3}$$

The reference force, R_r, gives a maximum stress in the stem equal to the modulus of rupture of green wood, S_r, for the species involved

$$R_r = \frac{\pi}{384} \frac{d_i^3 \quad S_r}{(H_{bh}-\bar{H}_{cp})} \cdot \frac{S_{bh}}{S_m} \tag{4}$$

The ratio of maximum stress, S_m, to that at breast height, S_{bh}, is given by Eq. (3.9) of Ref. 6 and depends on the fractional position of loading on the stem and the stem form factor, c.

$$\frac{S_m}{S_{bh}} = \frac{(f_m - f_1)}{(1 - f_1)} \left[\frac{(f_m + c)}{f_m(1 + c)}\right]^3 \tag{5}$$

where

$$\left.\begin{aligned} f_m &= C\left[1 - \left(1 - \frac{3f_1}{c}\right)^{1/2}\right], \quad \frac{3f_1}{c} \leq 1 \\ f_m &= 1 \qquad\qquad\qquad\qquad\quad\;\;, \quad \frac{3f_1}{c} > 1 \end{aligned}\right\} \tag{6}$$

The stem form is postulated to be hyperbolic. This is consistent with comprehensive studies on conifers which resulted in the basis for timber volume and growth tables of most all coniferous species in the United States. The stem form equation is

$$\frac{d}{d_{bh}} = \frac{H}{H_{bh}} \quad a\left[\left(\frac{H}{H_{bh}} + c\right)\right]^{-1} \tag{7}$$

and is used to calculate the stem diameter inside the bark at the base of crown, $d_c(H = H_c)$, and stem diameter inside the bark at breast height, $d_i(H = H_{bh})$.

The deflection energy modulus for maximum deflection at the center of pressure, $\bar{E}_1$, defined in terms of the reference force, is

$$\bar{E}_1 = \frac{k_r}{R_r^2} \int_0^{y_{max}} R(y)dy \tag{8}$$

where the theoretical spring constant for the stem, k_r, is given by Eq. (3.12) of Ref. 6 and also depends on the fractional position of loading on the stem and the stem form factor. This relationship for k_r is, however, not required in the blowdown prediction calculation.

The period of vibration of the tree is given by Eq. (2.3) of Ref. 6

$$\tau = a_\tau + b_\tau \, (H_{bh})^2/d_{bh} \tag{9}$$

and the weights of dry crown, branch wood, and foliage by Eq. (2.1) of Ref. 6

$$W_c = \frac{a_c (d_c)^{b_c}}{H_c} \text{ , etc} \tag{10}$$

To facilitate computation, the height to center-of-pressure relationship shown in Fig. 3.4 of Ref. 6 has been fitted in BLOWDOWN with a linear relationship*

$$\bar{H}_{cp} = 1.3d_c + 0.10H_c \cdot \frac{W_b}{W_f} \tag{11}$$

---

* Note: the relationship for broadleaf trees is

$$\frac{H_{cp}}{H_c} = a + bx + cx^2 + dx^3$$

where $x = \frac{H_{bh} \; d_c}{d_{bh}}$ and $a = 0.98865857$, $b = -0.17016963$,

$c = 9.271084(10)^{-3}$, and $d = -1.3239524(10)^{-4}$

and the various aerodynamic drag versus strain at base-of-crown relationships have been fitted by relationships of the type

$$\Psi = \frac{k_1 k_2 \left(\frac{R_r}{W_c}\right)^{-1.5}}{k_1 + k_2 \left(\frac{R_r}{W_c}\right)^{-1.5}} \tag{12}$$

so that

$$\Psi(o) = k_1 \tag{13}$$

That a tree stem will break or uproot under application of a given magnitude of force and deflection depends primarily on the size of the tree but also significantly on the intrinsic variability of the strength of tree stems and of root systems. Consequently, static measurements of tree failure have to be normalized so as to eliminate tree and stem dimensions. This is done by defining a deflection energy modulus for breakage, $\bar{E}_b$, analogous to the modulus of Eq. (8).

$$\bar{E}_b = \frac{k_r}{R_r^2} \int_o^{y_{break}} R(y)dy \tag{14}$$

For a given population, e.g., a particular type of tree stand or a particular class of growing conditions, the statistical distribution of $\bar{E}_b$ is determined by pulldown tests. Typical examples are shown in Fig. 2. Having thus determined the response of a given tree from Fig. 1, the probability of blowdown may be found from Fig. 2.

The constants used in Eq. (10) for determining weight of crown, foliage, and branchwood are found in Table II. These values are published here because values in previous references were incorrect due to a transposition of table columns. The values for k_1 and k_2 for Eq. (12) for broadleaf trees have not been previously published are are given in Table III.

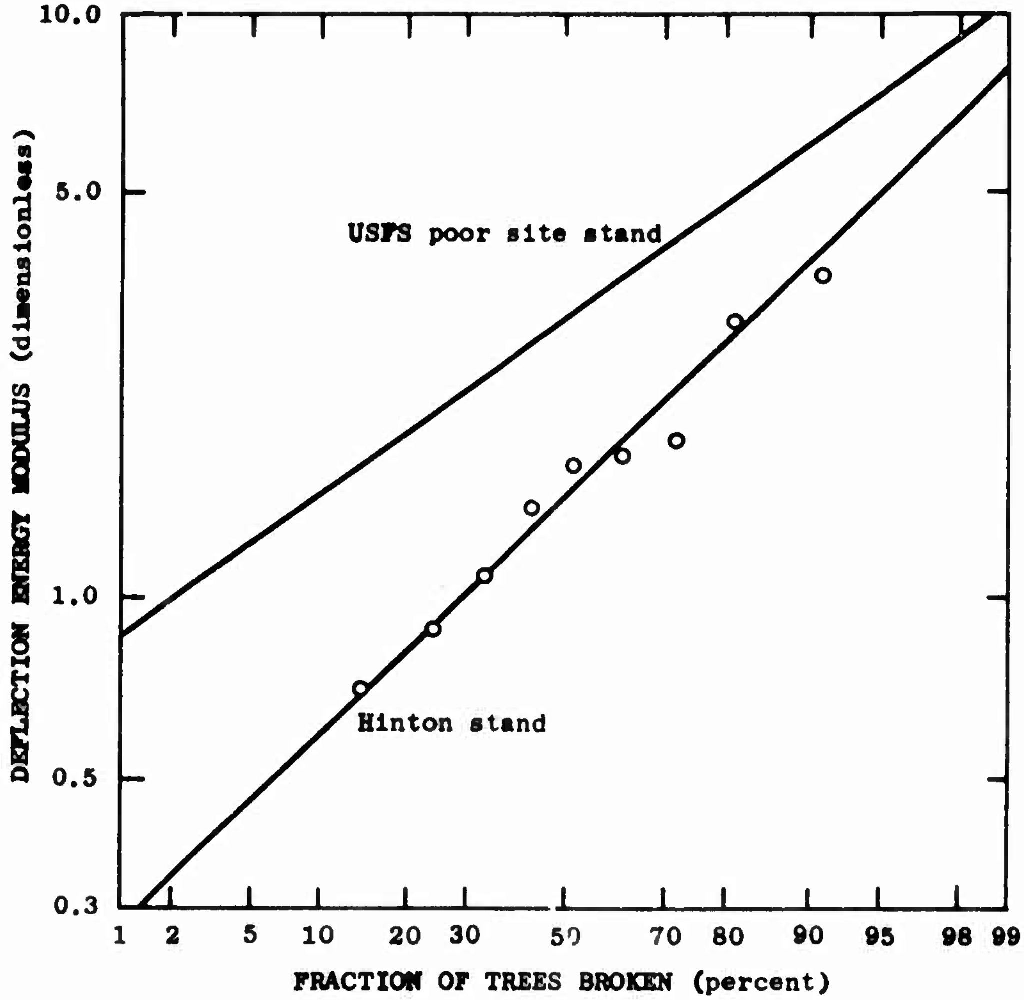

Fig. 2. Probability of Stem Failure Vs Deflection Energy Modulus - USFS Poor Site and Hinton Stand

Table II

VALUES OF CONSTANTS FOR EQUATION (10)

Tree Species and Location	Number of Trees	For Weight of dry crown When $W_o = W_c$		For Weight of dry branchwood When $W_o = W_b$		For Weight of dry foliage When $W_o = W_f$	
		a	b	a	b	a	b
Ponderosa pine (Calif.)	13	1.14	3.92	0.39	4.22	1.01	3.42
Sugar pine (Calif.)	4	1.81	3.46	0.54	3.86	1.30	3.09
Lodgepole pine (Calif.)	4	1.21	3.83	0.44	4.11	1.07	3.36
Loblolly pine (S. Car.)	9	9.11	3.11	3.10	3.45	6.28	2.74
White fir (Calif.)	9	2.77	3.51	0.81	3.78	2.23	3.23
Douglas-fir (Calif.)	6	3.34	3.52	1.00	3.88	2.52	3.10
Engelmann spruce (Idaho)	14	7.33	3.19	3.52	3.39	6.31	2.92
Incense cedar (Calif.)	6	2.58	3.53	0.80	3.76	2.51	3.19
Western larch (Idaho)	11	8.84	2.91	4.96	3.21	6.75	2.65
Silver maple	8	29.37	2.64	24.75	2.63	4.09	2.70
Sweet birch	10	16.76	3.14	13.15	3.19	3.58	2.90
Pignut hickory	10	30.21	2.96	24.31	2.98	6.41	2.75
American beech	8	35.99	2.82	27.71	2.89	9.28	2.38
Yellow-poplar	12	21.24	2.56	15.85	2.60	4.97	2.46
Scarlet oak	9	15.92	3.20	11.12	3.30	6.56	2.66

Table III

VALUES OF CONSTANTS k_1 AND k_2 FOR EQUATION (12)
(See also Table 6 and Equation 12 of Reference 1.)

Tree Type	k_1	k_2
Silver Maple	23,700	114,400
Sweet Birch	52,200	204,700
Pignut Hickory	115,000	442,400
American Beech	30,800	399,700
Yellow Poplar	31,600	213,300
Quaking Aspen	6,200	61,400
Scarlet Oak	56,500	172,400
California Black Oak	10,500	176,500

Design of the Analysis

The technique used in performing the sensitivity analysis is an approach that takes advantage of the mathematical expressions that exist for determining probability of blowdown. In general form, if the quantity U can be expressed as a function of independent variables, then

$$U = f(x_1, x_2, x_3) \tag{15}$$

Differentiating yields

$$dU = \frac{\partial U}{\partial x_1} dx_1 + \frac{\partial U}{\partial x_2} dx_2 + \frac{\partial U}{\partial x_3} dx_3 \tag{16}$$

and dividing by U yields

$$\frac{dU}{U} = \frac{\partial U}{\partial x_1} \frac{dx_1}{U} + \frac{\partial U}{\partial x_2} \frac{dx_2}{U} + \frac{\partial U}{\partial x_3} \frac{dx_3}{U} \tag{17}$$

Thus the change in U with respect to U, (dU)/U, can be determined for a change in x_1, x_2, or x_3 by evaluating each term in Eq. (3). For example, the weight of a tree crown is determined by the following expression

$$W = \frac{a(d)^b}{H} \tag{18}$$

where a and b are species-dependent constants, d is the diameter of the stem at the base of the crown, and H is the tree height. By means of the approach illustrated in Eqs. (15) through (18), the following is obtained:

$$\frac{dW}{W} = (\frac{da}{a}) + b\ (\frac{dd}{d}) + b \log_e d\ (\frac{db}{b}) - \frac{dH}{H} \tag{19}$$

The effect on W can now be determined for any change in an input parameter. For example, for

$a = 1.14$ $\qquad$ $d = 5$

$b = 3.92$ $\qquad$ $H = 20$

a and b are for Ponderosa pine, and where

$$\frac{da}{a}, \frac{db}{b}, \frac{dd}{d}, \frac{dH}{H} = 0.02$$

the following results are obtained:

Variable	Change (%)	Change in W (%)
a	2	+ 2
b	2	+12.6
d	2	+ 7.8
H	2	- 2

Therefore, it can be concluded that the value of W is most sensitive to variations in the exponent b and the diameter of the stem. There is one difficulty with this approach: there is no mathematical expression for determining the tree deflection energy modulus, $\overline{E}_1$, or the maximum energy absorbed by the tree, using the values of strength and duration of the airblast, and the natural period and drag characteristics of the tree crown. This is accomplished in the computer model through an interpolation routine operating on the digitized curves of Fig. 1. This difficulty was surmounted by using finite differences rather differential changes. This technique is valid for sufficiently small values of finite differences. The set of differential equations programmed on a computer time sharing system for the sensitivity analysis is given in Appendix A.

Ground range was chosen as the output parameter to be monitored. As the ultimate output of the computer model BLOWDOWN is a probability of blowdown for a given overpressure, modifications had to be made to convert this result into ground range.

The results were output in the form of a computer-generated plot of the variation in ground range for a specified probability of blowdown as a function of variation in the specified input parameter. However, prior to performing this calculation, a set of initial conditions had to be specified. Altogether, five basic sets of initial conditions, or values of input parameters, were used in the test matrix. These consisted of initial values for conifer trees and broadleaf trees representing forests with heights of 40 ft, 120 ft, and for broadleafs only, heights of 200 ft.

Calculations were performed for a yield of 1 KT, then repeated for the most sensitive parameters with an initial value of yield equal to 1 MT. The initial values of the input parameters for the five basic sets of calculations are given in Table IV. The nomenclature for the parameters is the same as that used in the BLOWDOWN program and is given in Table I. It should be noted that parameters A2 and B2 are not used in calculations for broadleaf tree response, therefore, their values have been set at zero. The values of overpressure are estimates of the overpressure required for 0.5 probability of blowdown. The computer program performs an iteration procedure to determine the correct value of overpressure prior to performing the sensitivity analysis. The parameters Y5 and Y6 are the $\log_{10}$ of the mean and standard deviation, respectively, of the probability distribution of breakage for values of EB. Referring to Fig. 2, the probability of breakage or fraction of trees broken is seen to be a log normal distribution. Therefore, variations in the log of the mean or the log of the standard deviation will cause, respectively, shifts in the horizontal and vertical location of the curve, and changes in the slope.

The procedure used consisted of the following steps. First, plots were obtained of the variation in ground range for 50 percent probability of blowdown as a function of the variation in each input parameter. The variation in input parameter values was generally restricted to ±10 percent of initial value, and the calculations were performed for an initial value of yield of 1 KT. The variation in ground range for variations in the parameter Y6 was determined for 20 percent probability. This was because a change in the slope of the probability distribution does not change the mean value or the 50 percent probability value of EB. Therefore, no change in ground range would occur. In the second step of the procedure, the results of these calculations were analyzed and calculations of the most sensitive input parameters were repeated for an initial value of yield of 1 MT.

Table IV

INITIAL VALUES OF INPUT PARAMETERS FOR THE FIVE BASIC SETS

Tree Type	Conifer	Conifer	Broadleaf	Broadleaf	Broadleaf
A	0.74	0.74	0.6	0.6	0.6
B	0.7	0.7	1.0	1.0	1.0
A1	3	3	24	24	24
B1	3.5	3.5	2.9	2.9	2.9
A2	0.4	0.4	0	0	0
B2	0.75	0.75	0	0	0
A3	0.94	0.94	1.68	1.68	1.68
B3	0.0067	0.0067	0.007	0.007	0.007
SR	7,000	7,000	8,000	8,000	8,000
K1	5,000	5,000	33,000	33,000	33,000
K2	50,000	50,000	160,000	160,000	160,000
AH3	0.8	0.8	0.8	0.8	0.7
BHB	5	10	5	5	40
DB	4	20	6	36	80
HB	40	120	40	120	200
Z	1.0	1.0	1.0	1.0	1.0
P_s	9.5	30	3.5	3.5	3.5
Y5	0.25	0.25	0.09691	0.09691	0.09691
Y6	0.235	0.235	0.190704	0.190704	0.190704

Results

The results from the B-120-1 calculations are shown in Figs. 3 through 10.* The plots from all calculations are not given so as to conserve space, but the results from all plots similar to those in Figs. 3 through 10 are summarized in Table V.

As can be seen, the plots are normalized about the initial values of the input parameters and the value of ground range for 50 percent probability of blowdown determined from the initial values of the input parameters. Therefore, as the normalized value of the input parameter varies from 1.0 to 1.1 and from 1.0 to 0.9, or ±10 percent; the change in ground range can be determined. There are other features of the plots which merit explanation.

Some of the plots have "kinks" which one would not expect for smoothly varying functions. These are caused primarily by the interpolation procedure used with the digitized curves of Fig. 1 and the necessity to approximate a differential change in $\bar{E}$, with a finite difference. Some plots do not cover the full range of ±10 percent variation in the input parameter because of a built-in limit on computing time which would permit the generation of sufficient information to display well-established trends, but would eliminate excessive computer calculation time. In such cases, extrapolated curves were fitted by eye.

The summary of results presented in Table V indicates the variation in ground range for a +10 percent or -10 percent variation in the value of the input parameter. For example, a +10 percent variation in the value of A2 for a C-40-1 calculation results in a -5.8 percent change in ground range.

* Calculations are identified as follows: the letter refers to the tree type, B for Broadleaf, C for Conifer; the first number refers to the tree height in feet; the last number to the weapon yield in kilotons. Thus, B-120-1 means a 120-ft high, Broadleaf forest subjected to a 1 kt burst.

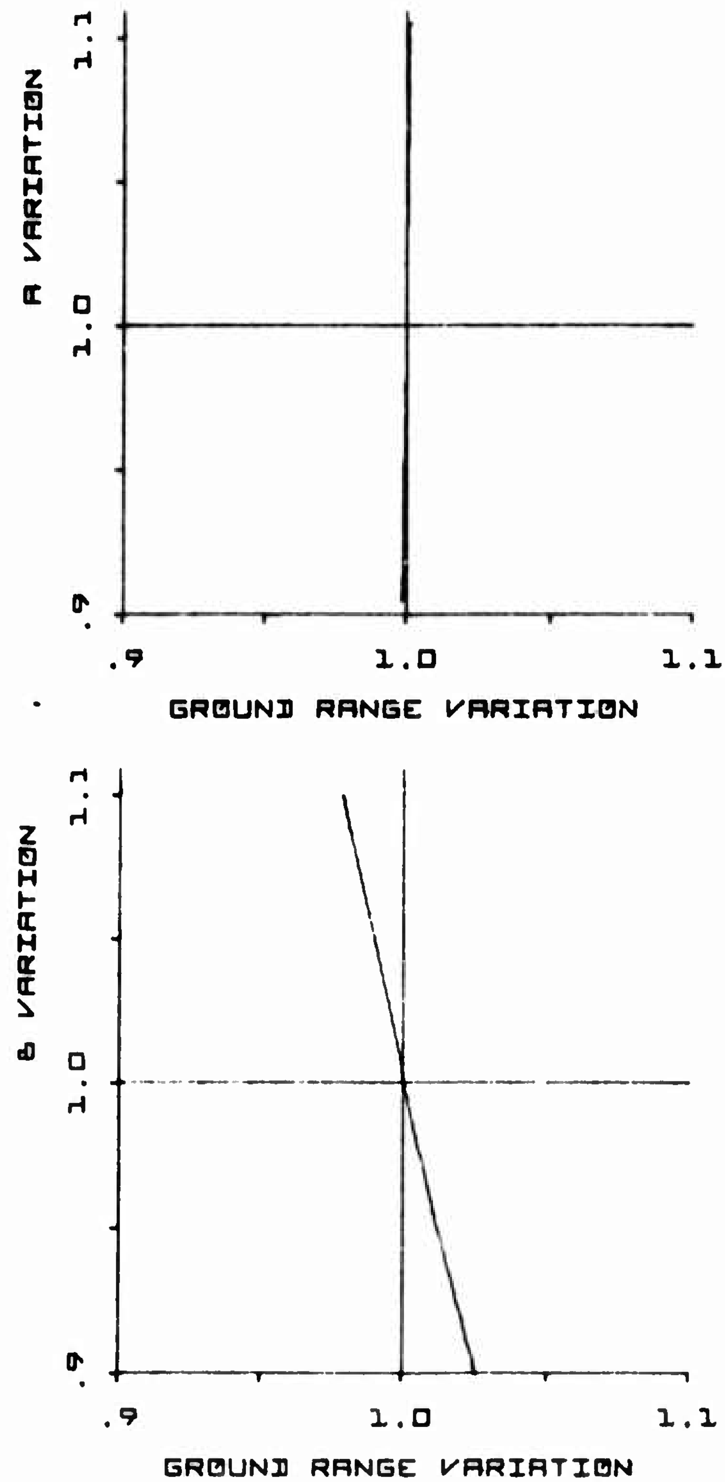

Fig. 3. Sensitivity to Variations in Parameters A and B

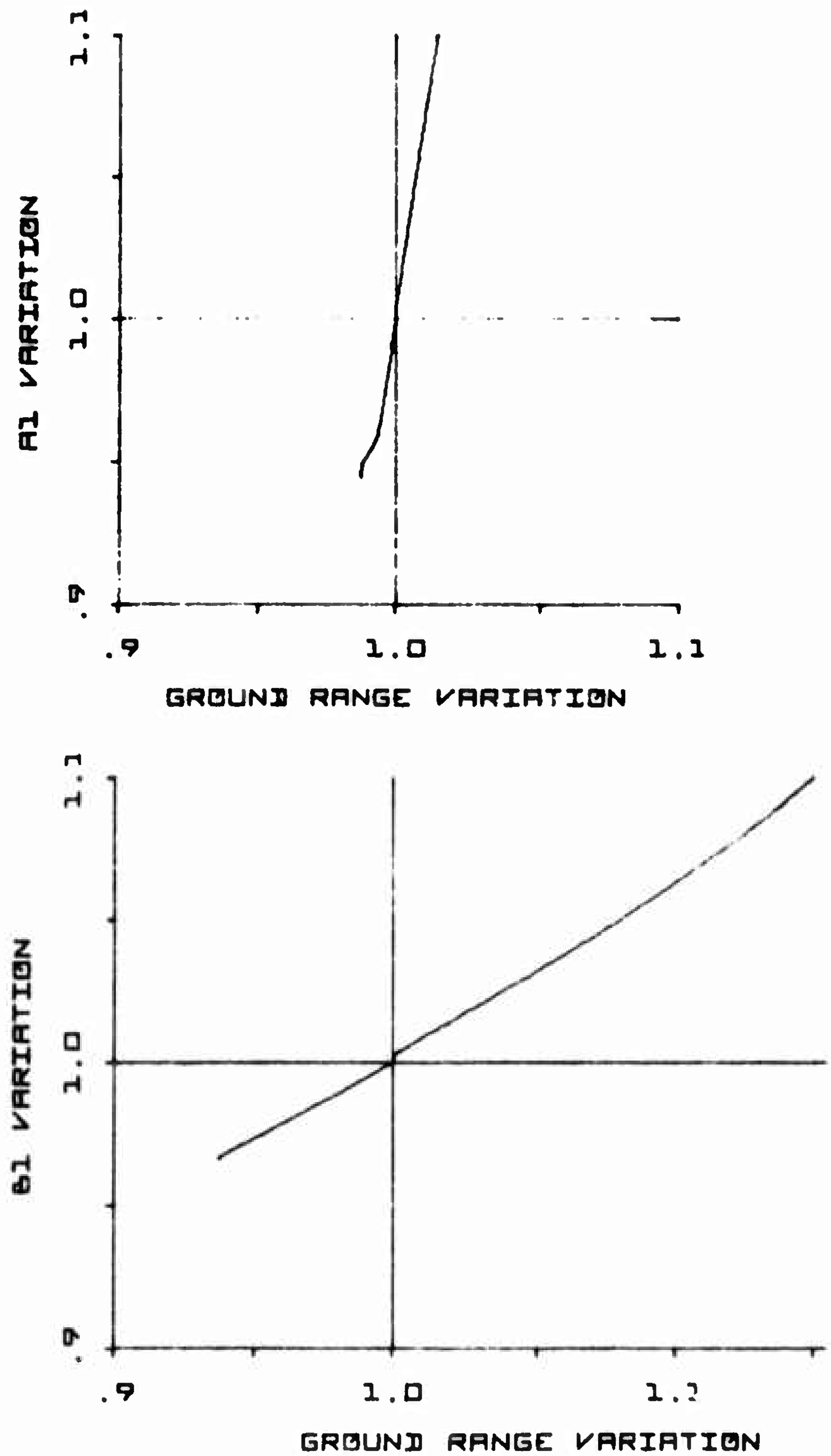

Fig. 4. Sensitivity to Variations in Parameters A1 and B1

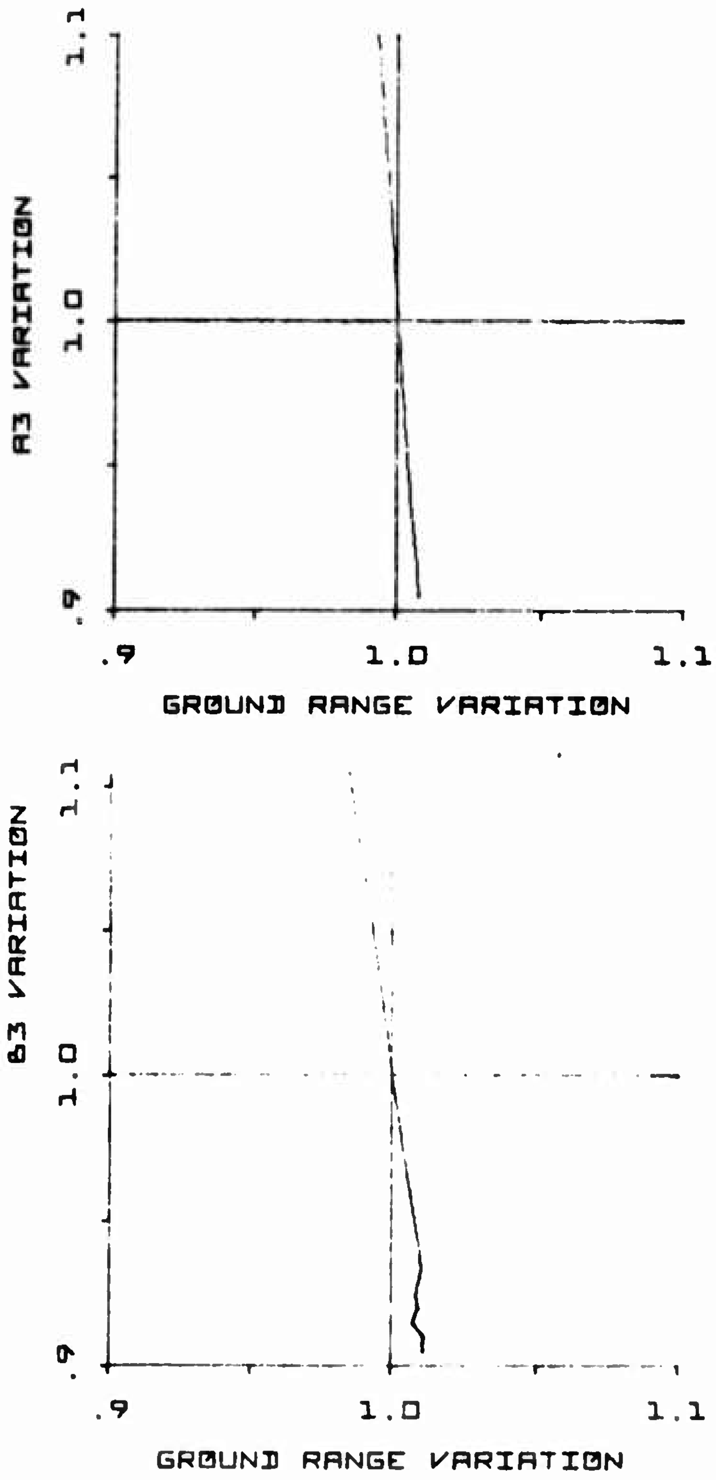

Fig. 5. Sensitivity to Variations in Parameters A3 and B3

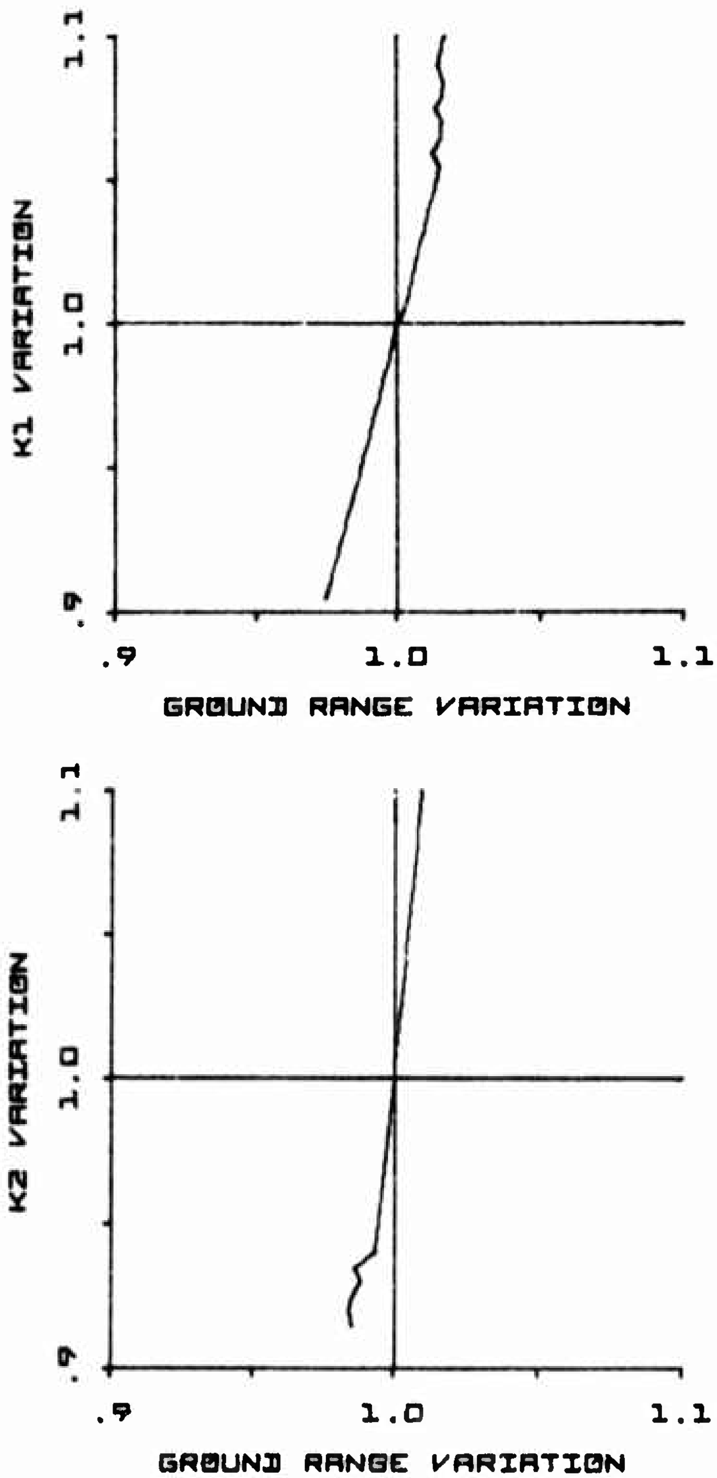

Fig. 6. Sensitivity to Variation in Parameters K1 and K2

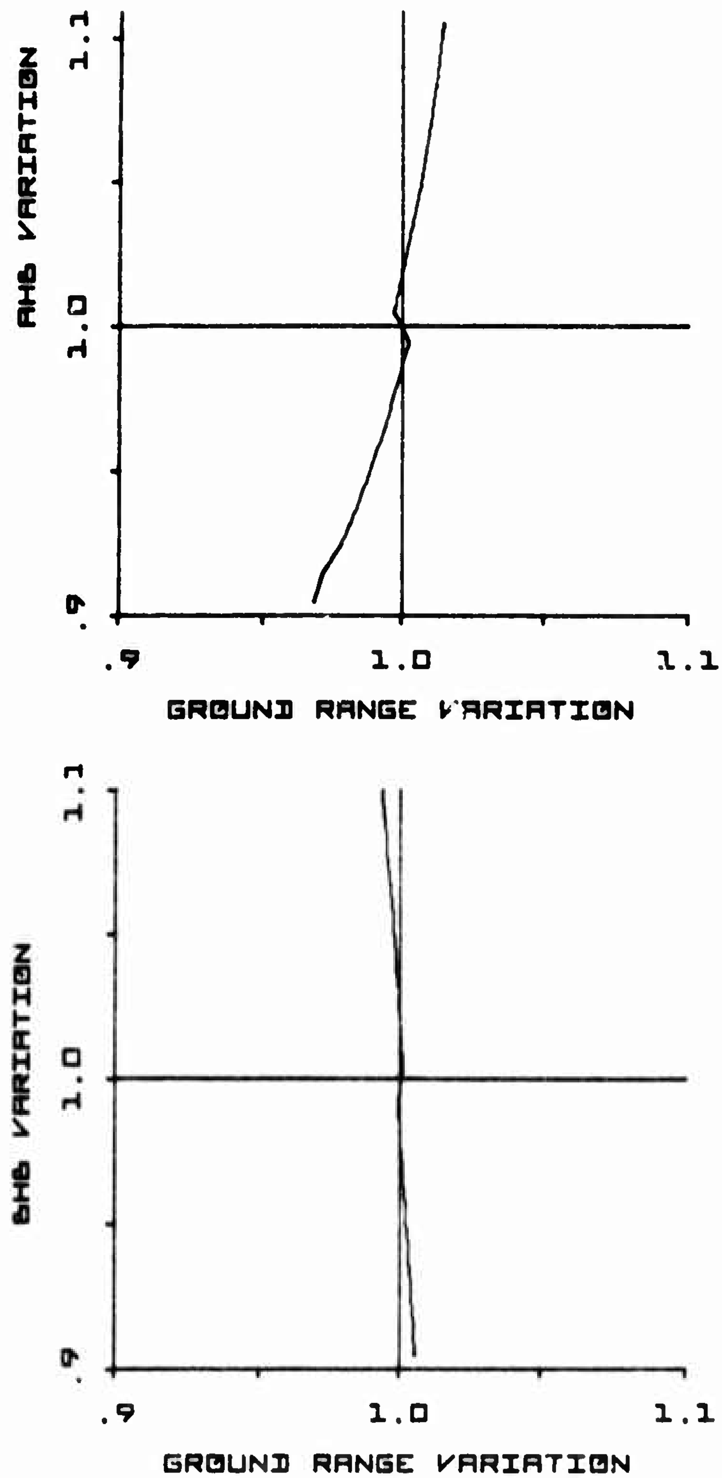

Fig. 7. Sensitivity to Variations in Parameters AHB and BHB

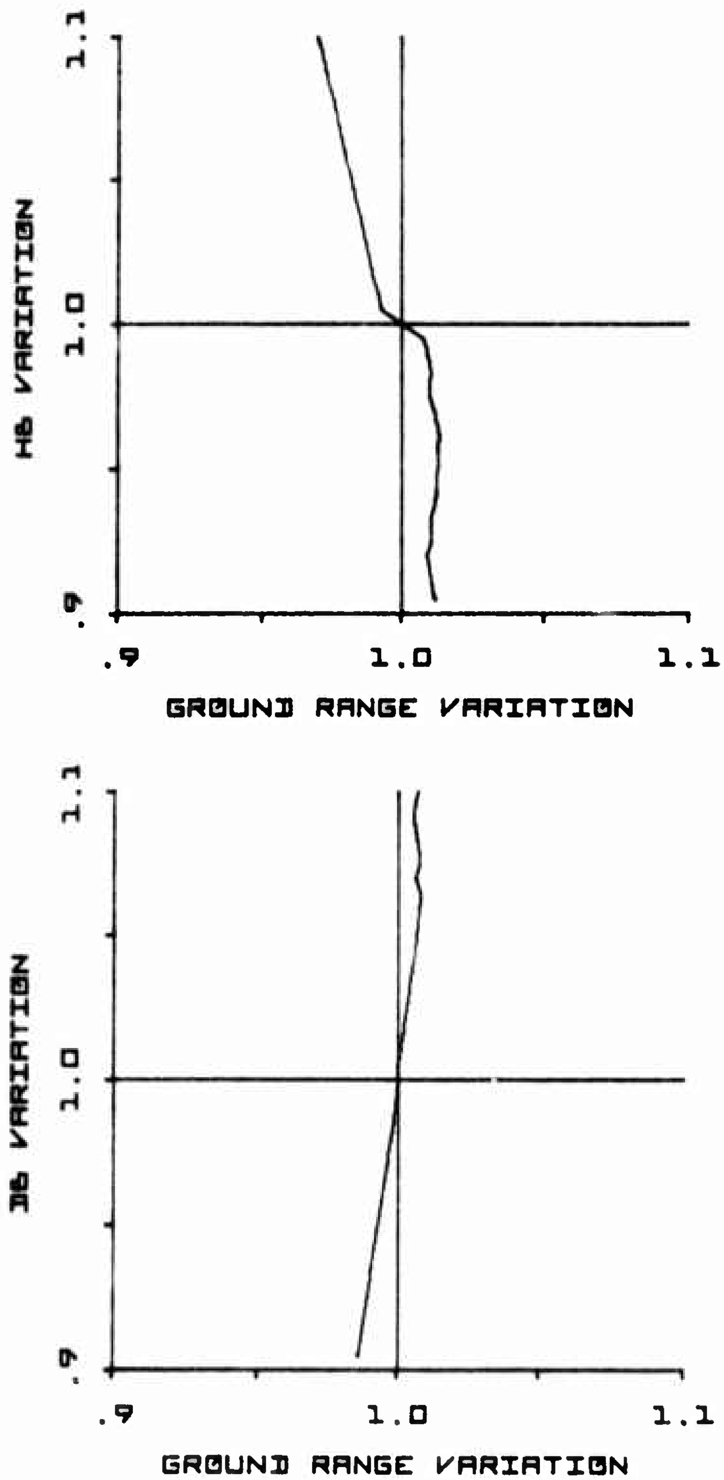

Fig. 8. Sensitivity to Variations in Parameters HB and DB

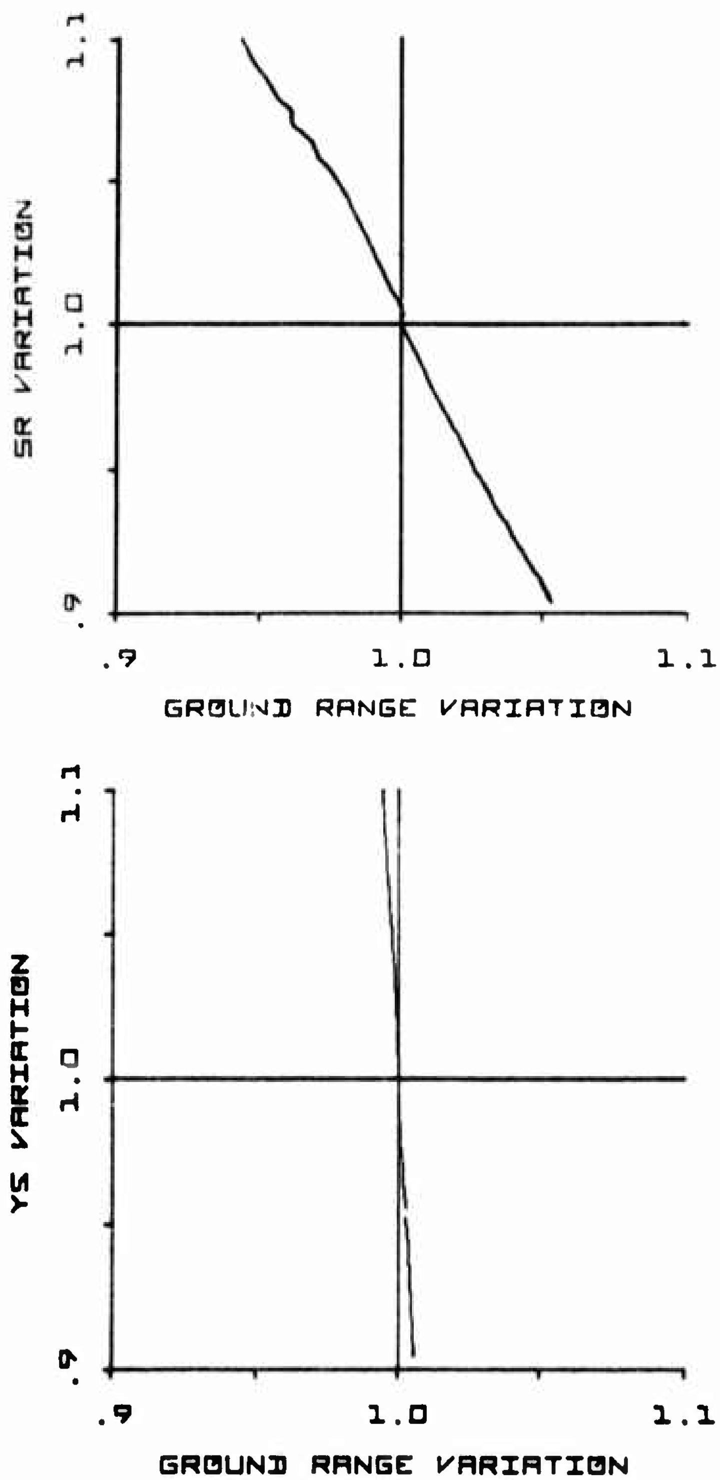

Fig. 9. Sensitivity to Variations in Parameters SR and Y5

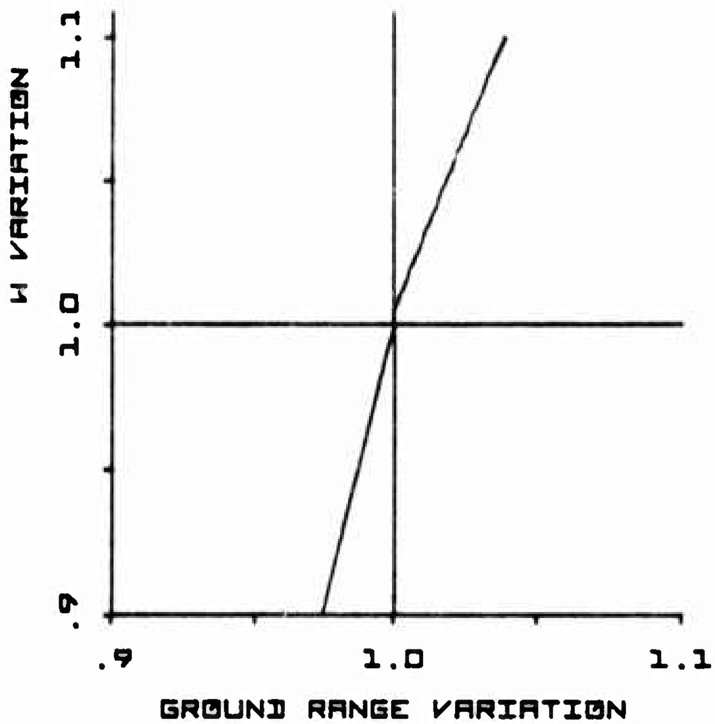

Fig. 10. Sensitivity to Variations in Yield

Table V

SUMMARY OF SENSITIVITY ANALYSIS RESULTS

Input Parameter	Conifer, H = 40 ft				Conifer, H = 120 ft				Broadleaf, H = 40 ft				Broadleaf, H = 120 ft				Broadleaf, H = 200 ft			
	(1KT)		(1MT)		(1KT)		(1MT)		(1KT)		(1MT)		(1KT)		(1MT)		(1KT)		(1MT)	
	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
A	+6.6	-6.6	+5.8	-6.3	+2.8	-2.8	NS	NS	-1.4	+2	NS	NS	*	*	NS	NS	*	*	NS	NS
B	+6.8	-6.9	+6.6	-6.9	*	*	NS	NS	-1.8	+2.2	*	+1.2	*	*	NS	NS	-2.1	+2.5	NS	NS
A1	+1.5	-3.4	+2.3	-3.1	*	-3.3	NS	NS	+1.2	-1.6	NS	NS	+1.2	-1.6	NS	NS	+1.2	-2.5	NS	NS
B1	+3.7	-15	+10.9	-8.9	+7	-18	+14	-24.3	+6	-9	+11	-12	+12	-16	+27	-27	+14.8	-19	+30.5	-35
A2	-5.8	+6.8	-5.2	+6.4	-5.1	+6.1	-3.4	+4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B2	-4.6	+5.1	-4.4	+4.8	-10.3	+10.3	-7	+7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A3	*	*	NS	NS	-1.1	+1.1	NS	NS	-1.1	+1.2	NS	NS	*	*	NS	NS	*	*	NS	NS
B3	-1.7	*	NS	NS	-5.2	+2.8	NS	NS	-1.2	+1.3	NS	NS	-1.4	+1.6	NS	NS	-1.6	+1.5	NS	NS
SR	-6.6	+6.4	-5.6	+6.9	-7.3	+7.5	-3.1	+6.6	-4.4	+5.3	-5.6	+6.6	-9.4	+10.5	-5.8	+7.2	-5.7	+5.6	-5.1	+7.8
K1	*	-3.1	NS	NS	+3.2	-7.3	+2.3	-2.6	+2.4	-2.6	+1.2	-1.5	+2.4	-2.8	NS	NS	+2	-2.7	*	*
K2	-1.2	-2.8	NS	NS	*	-1.7	NS	NS	*	*	NS	NS	*	*	NS	NS	*	-2	NS	NS
AHB	-4.1	+4.7	-4	+4.7	-3.9	+2.1	NS	NS	-3	+1.6	NS	NS	-3.9	+2.7	-5	+3.6	+1.4	-3.3	+2.5	-3
BHB	*	*	NS	NS	*	*	NS	NS	*	*	NS	NS	*	*	NS	NS	*	*	NS	NS
DB	-5.7	+5.6	-5	+6.5	*	-2.2	*	*	*	-1.1	NS	NS	+1.2	-1.5	NS	NS	*	-1.5	NS	NS
HB	-1.9	*	NS	NS	-12	+10.2	-3.5	+3.2	*	+1.2	NS	NS	-3.2	+3.7	-1.2	+1.5	-3	+1.5	NS	NS
Z	-2.8	-2.7	NS	NS	+4.6	-1.1	NS	NS	+3.9	-2.5	+3.2	-3	+3.8	-2.5	NS	NS	+3.9	-2.5	+3.3	-3
Y5	-1.5	*	NS	NS	-2.2	+1.4	NS	NS	*	*	NS	NS	*	*	NS	NS	*	*	NS	NS
Y6	+1.2	-1.4	NS	NS	*	-2.1	NS	NS	*	*	NS	NS	*	*	NS	NS	*	*	NS	NS

NA - Not applicable
NS - Not significant, not calculated for 1mt case
* - Variation < = 1%

Discussion

In the following, the results of the sensitivity analysis results are discussed from two points of view. The primary one is the design of a sufficiently accurate forest blowdown prediction within the constraints of overall model accuracy. Within this context, the objective is to determine the minimum amount of input information required. The second point of view is the priority for obtaining additional tree characteristic data to refine and improve the accuracy of input data for computer model predictions.

Based on the results summarized in Table V, a significant number of variables can be excluded from further discussion because the output of the computer model is virtually insensitive ($\leq$ a 5 percent change in output) to changes in these variables. The discussion of each variable is headed by the variable name using Ref. 2 nomenclature and Ref. 6 nomenclature, and the number of the applicable equation, if any, given in Section IV.

A(a), Eq. (7), stem form factor - This factor has greatest significance for short trees, particularly conifers. For the C-40-1 calculation, a 10 percent change resulted in a 6.6 percent change in ground range. For the B-40-1 calculation, a -1.4 percent and +2 percent change resulted for a +10 percent and -10 percent input variation. However, the magnitude of the output change decreases as the tree height or detonation yield increases. For the majority of forests and yields, this parameter would not be of much significance.

B(c), Eq. (7), stem form factor - This parameter behaves in a manner very similar to its companion parameter, A, both in magnitude and trends.

B1(b_c), Eq. (10), crown weight factor - The analysis results show this parameter to be consistently the most significant of all input factors. Its significance increases with yield and tree height.

A2(W_b/W_f), Eq. (2), crown weight ratio factor where $W_b/W_f = A2(DC)^{B2}/HC$ - This factor is not used in calculations for broadleaf trees. Its significance for conifers decreases as yield and tree height increase. As the magnitude of the output change is on the order of ±5 percent on the average, this parameter is considered marginally significant.

B2, crown weight ratio factor (see explanation of parameter A2) - The model output is significantly sensitive to the value of this input parameter. The smallest output change is -4.4 percent for a +10 percent change in input for the C-40-1000 calculation, and the largest is a ±10 percent output change for a ±10 percent input change for a C-120-1 calculation. The magnitude of output change appears to increase with an increase in tree height, and decrease with an increase in yield.

SR(S_r), Eq. (4), modulus of rupture - This parameter is consistently significant and usually ranks in the first three most significant parameters. Its greatest influence on input occurs in the B-120-1 calculation and its smallest in the C-120-1000 calculation. No general trends seem apparent in examining these results.

HB(H_{bh}), Eq. (7), length of tree above breast height - This parameter seems to have a greater significance for conifer trees than for broadleafs. The magnitude of output change is on the order of 2 to 3 percent and is not considered significant for broadleafs. More detailed caclulations showed that increasing broadleaf tree height from 40 ft to 120 ft decreases ground range on the order of from 9 to 10 percent. The significance of this parameter for conifer trees is somewhat larger. The greatest effect on output was for the C-120-1 calculation where a ±10 percent change in input resulted in a -12 percent and a +10.2 percent change, respectively, in output. For this calculation, HB was the second most significant parameter.

Z(W), yield - The magnitude of the output changes for variations in this input parameter are fairly consistent. However, the ranking of its significance was higher for broadleafs than for conifers. In other words, the magnitude of the output change is on the order of 3 to 4 percent. However, it was generally the third most important input parameter for broadleaf calculations, whereas its ranking for conifers was ninth or eleventh. Changing yield from 1 kt to 1 mt increases ground range about 50 percent for broadleafs, and about 70 percent for conifers.

Y5 and Y6, breakage probability distribution parameters - The results of the sensitivity analysis indicate that ground range is not sensitive to ±10 percent variations in these parameters. However, the deflection energy modulus for 50 percent probability may change as much as a factor three between "good site" and "poor site" conditions. Significant changes in ground range would result from changes in input of this magnitude.

Summary

The input parameters to which prediction of blowdown for both broadleaf and conifer trees is most sensitive are 1) the exponent of the crown weight relationship, 2) the modulus of rupture of the tree, 3) yield, and 4) site conditions, i.e., "good" site vs "poor" site. In addition, the conifer results are sensitive to 1) tree height, and 2) the exponent of the relationship for the ratio of branch weight to foliage weight. The broadleaf results are not sensitive to tree height.

In summary, the most important parameters for determining the ground range for a given probability of blowdown are B1, SR, and Z for broadleaf trees, and B1, B2, SR, HB, and Z for conifers. In addition, the differences between "good site" and "poor site" conditions significantly affect BLOWDOWN results.

Section V
DEVELOPMENT OF PREDICTION TECHNIQUE

Assumptions and Approach

The overall approach to the development of a forest damage prediction technique is to incorporate the current state-of-the-art within the constraints of the data available to the investigator making the prediction, the accuracy required, and the uses of the predicted results. The current state-of-the-art is embodied in the computer model BLOWDOWN, and the sensitivity analysis described in Section IV of this report provides the information needed in assessing the accuracy of results obtainable with input data of varying completeness.

The information generally considered available to commanders in the field from ground and/or aerial reconnaissance is average tree height and diameters, tree density, tree type (i.e., broadleaf vs conifers), and site conditions. Tree density and diameter are not required to determine probability of blowdown; however, they are required to determine the effects of the forest blowdown zone on movement of troops and vehicles (see Ref. 7). The site conditions are more easily determined from ground reconnaissance and are discussed in terms of topsoil depth and moisture content. The determination of site conditions by aerial photo reconnaissance strongly depends on the ability of the photo interpreter. Thus the identification of "good" and "poor" site conditions is possible. "Good" and "poor" site conditions have been described in Ref. 6 and are summarized below.

> Good Site - Characterized by well-drained soil layer that is deep and generally free of rocks. Adequate precipitation is available with temperatures favorable for a long growing season. Generally, north-facing slopes, valleys, and well-drained flats are good locations, in the middle elevations and latitudes.

Poor Site - Characterized by wet or poorly drained soil and/or shallow soil with a large amount of rocks or silt content. Deficient annual rainfall, and a short growing season such as at the higher altitudes and lower latitudes. Poor growing conditions can be characterized also by arid ridges, poorly drained flats, and steep south-facing slopes.

The sensitivity analysis revealed that some specie-dependent parameters are required to obtain acceptable accuracy in blowdown predictions (in this case 90 percent probability of predictions within ±15 percent of actual ground range for particular percentage blowdown). The sensitivity analysis also reveals that a rather broad categorization of species would achieve acceptable accuracy. With some training and/or experience, it should be relatively easy to make this determination with ground reconnaissance. Reference 9 states that specie identification from aerial photographs is possible, but requires large scale aerial photographs.

Analysis of specie-dependent parameters indicates that both conifer and broadleaf trees can be grouped into two broad classes; light crowned and heavy crowned. There is significantly more data available for conifer trees than for broadleaf, particularly for defoliated broadleaf. Therefore, greater confidence must be placed on the conifer groupings. The descriptions of the specie groupings are given below.

- Conifer, Class I - light crowned conifers consisting of spruces, cedars, hemlocks and larches. Needle length generally less than 2-1/2 in., medium shade tolerance, and needle persistence on the order of 3 years.

- Conifer, Class II - heavy crowned consisting of most pines and firs. Needle length generally greater than 2-1/2 in., with less shade tolerance than Class I conifers, and needle persistence averaging 5 years.

- Broadleaf, Class I - characterized by trees with generally small leaves such as birches, poplars, and scarlet oak.

- Broadleaf, Class II - characterized by trees with generally large leaves such as beeches, hickory, maples.

- Broadleaf, Defoliated - all broadleafs in a defoliated condition.

The categorization of forest damage in terms of the percent of trees down is insufficient to quantitatively evaluate the effects on movement of troops and vehicles. Reference 8 incorporates the analysis of Ref. 7 into a prediction technique for determining effects on movement, and, although data are limited, it is well demonstrated that data on the number of stems down per acre and diameter of stems down is required for this prediction However, the effects on movement are not dependent upon a simple relationship depending on these two parameters. The effects also depend on the direction of travel, either radially inward toward or outward away from GZ and circumferentially, the type of vehicle or type of troop movement, and (particularly for troop movement) the amount of visibility. The incorporation of these factors into the determination of damage categories would be complex and somewhat self-defeating. The approach adopted consists of simply defined damage categories for forest damage supported with extensive descriptive material sufficient to orient and familiarize the investigator, and additional information with which more precise effects on movement can be determined for a particular forest environment.

The definitions of forest damage which were adopted are as follows:

Light damage - 10 percent of trees down. Little impediment to movement likely. For forests with large secondary growth, underbrush or vines, some improvement over virgin forest conditions possible due to improved visibility.

Moderate damage - 50 percent of trees down. Significant effect on movement of troops, especially in units. Greater effect in damaged broadleaf forest because of greater amount of branch debris. Slowing of vehicles possible, particularly for forests of high density.

Severe damage - 90 percent of trees down. Severe obstacle to troop movement in units or individually. Substantial probability of stopping wheeled vehicles, and slowing of tracked vehicles, depending on forest density.

Destroyed - essentially all vegetation removed. No impediment to visibility or movement.

In accordance with the previous discussions, calculations were performed to determine the overpressure level as a function of yield required for 10, 50, and 90 percent of trees down for conifers Class I and II, broadleaf Class I and II, and defoliated broadleaf. Good and poor site calculations were performed for both conifer and broadleaf classes with average site conditions used for the defoliated broadleaf forest calculation. Average site conditions were used because of the relative scaracity of data for defoliated broadleaf trees. In addition, a further breakdown of conifers by tree height as indicated by the sensitivity analysis was included. The results of these calculations are presented in Appendix B, Figs. 15-1 through 15-7.

An independent check of the validity of these curves and an example of their use can be provided by attempting to predict the results of Operation DISTANT PLAIN, Shot 4. The forest at Hinton consisted primarily of lodgepole pine with fir and some spruce (conifer, Class II) on a poor site (Ref. 7). Shot 4 was a 50 ton HE surface burst. If it is assumed that 50 tons HE is equal to 100 tons nuclear, Fig. 15-7 can be used. The average height of the forest was 52 ft. The overpressures for 50 percent of trees down for forests of 40 ft and 80 ft height are 8.9 psi and 13.7 psi, respectively. Interpolating for a height of 52 ft yields an overpressure of 10.3 psi. From Ref. 12, the scaled ground range for this overpressure from a surface burst is 1000 ft. Scaling to 100 tons results in a ground range of 464 ft. From Ref. 10, the ground range for 50 percent of trees down was actually 444 ft. This is a +4.5 percent difference. Calculations for 10 percent and 90 percent down give ground ranges which are +7 percent and +5.8 percent different from the observed. This is considered a very good correlation.

The foregoing technique for predicting ground range for 10, 50, and 90 percent of trees down for various forest types and condition, plus the prediction technique presented in Ref. 8 for predicting effects on movement, forms the basis of the prediction technique presented in the following material.

Prediction Technique

The descriptive material, definitions, and technical data required to assess and predict the effects of airblast on forests is given in Appendix B.

Section VI

CONCLUSIONS AND RECOMMENDATIONS

In the broadest sense, the sensitivity analysis confirms the impulsive mode of tree loading and response upon which the model is based. This is supported by the general observation that the influence of variation in individual parameters on model results decreases as yield increases. Conversely, sensitivity to input variations increases with a decrease in yield. It is therefore fortunate that the model was verified using fractional KT high explosive data where sensitivity to input variables is greatest.

The conclusions and recommendations of this report are based upon the results of the sensitivity analysis and the development of the prediction technique. The latter, naturally embracing a larger scope than the sensitivity analysis, highlighted certain limitations of the state-of-the-art which are addressed in the recommendations.

The general conclusions of this effort are:

1. The blowdown model is most sensitive to the following input parameters, in order of importance.
    a. Detonation yield and forest growing conditions.
    b. The specie-dependent parameters of modulus of rupture of the tree wood, and the exponent of the crown weight relationship.
    c. Results for conifer forests are also sensitive to tree height, and the exponent of the relationship for the ratio of branch weight to foliage weight.
    d. Results for broadleaf forests are not sensitive to tree height.

2. The data generally available from air and/or ground reconnaissance is adequate to perform blowdown predictions of sufficient accuracy.

3. Data on the characteristics of broadleaf trees is not as extensive as for conifer trees, thereby reducing the comparative reliability of broadleaf blowdown predictions.

4. Data on the effect of broadleaf tree growing conditions on tree failure is not as extensive as for conifer tree growing conditions, thereby reducing comparative reliability of broadleaf blowdown predictions.

5. Data are sparse on the drag characteristics of defoliated broadleaf trees, and nonexistent for conifer trees.

6. The effect of growing conditions on the failure of defoliated trees is not known.

7. Insufficient analysis of the data on hand clearance of blowdown debris, and the virtual nonexistence of machine clearance data and analysis precludes the quantification of debris clearance rates for a variety of forests.

The recommendations of this report are that:

1. The prediction technique developed in this report (Appendix B) be adopted and published in Defense Nuclear Agency's Effects Manual No. 1.

2. The loading and response of trees in the regular reflection region be determined.

3. The effects of thermal radiation phenomena on tree loading and response be determined.

4. Additional data on the characteristics of broadleaf trees be obtained.

5. Additional data on the crown drag characteristics be obtained for defoliated trees.

6. A determination be made of the effect of growing conditions on the response of defoliated trees.

7. Additional data be obtained and analysis be performed to enable quantification of debris clearance by hand and machine methods as a function of debris characteristics.

8. Additional data be obtained and analysis be performed to enable quantification of troop movement rates as a function of debris characteristics. The reliability of vehicle movement degradation by blowdown debris should be improved.

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Appendix A

MATHEMATICAL RELATIONSHIPS FOR SENSITIVITY ANALYSIS OF U.S. FOREST SERVICE FOREST BLOWDOWN MODEL

The probability of tree failure is determined from the value calculated for EB, the deflection energy modulus.* Where

$$EB = f(x,y)$$

where

$$x = \frac{0.23Q\ (QRO)\ T}{QR\ (IQ)} \tag{A-1}$$

and

$$y = \frac{Q}{QR} \tag{A-2}$$

since

$$QR = \frac{M}{J},\ \text{and} \tag{A-3}$$

$$QRO = \frac{M}{K1} \tag{A-4}$$

Eqs. (A-2), (A-3), and (A-4) can be substituted into Eq. (A-1) with the result

$$x = \frac{0.23Q\ (T)\ J}{IQ\ (K1)} \tag{A-5}$$

---

* Nomenclature is same as that given in Ref. 2.

Similarly

$$y = \frac{QJ}{M} \tag{A-6}$$

In order to determine sensitivity, it is necessary to know what effect changes in the values of input parameters have on the values of output parameters. Therefore, the change in x and y with respect to their base values as a function of small changes in input parameters is required. Thus the values of dx/x and dy/y are necessary.

Taking the expression for y first

$$y = \frac{QJ}{M}$$

Differentiating and dividing by y yields

$$\frac{dy}{y} = \frac{d\ (QJ)}{QJ} - \frac{dM}{M} \tag{A-7}$$

Taking each term seperately

$$d\ (QJ) = du = \frac{\partial u}{\partial Q}\ (J)\ dQ + \frac{\partial u}{\partial J}\ (Q)\ dJ$$

where u = QJ. Dividing by the term QJ yields

$$\frac{d\ (QJ)}{QJ} = \frac{\partial u}{\partial Q}\ \frac{\partial Q}{\partial P}\ \frac{dP}{JQ} + \frac{\partial u}{\partial J}\left[\frac{\partial J}{\partial K1}\ dK1 + \frac{\partial J}{\partial K2}\ dK2 + \frac{\partial J}{\partial G}\ (G)\ \frac{dG}{G}\right]\frac{1}{JQ} \tag{A-8}$$

where

$$dQ = \frac{\partial Q}{\partial P}\ dP$$

and

$$dJ = \frac{\partial J}{\partial K1} dK1 + \frac{\partial J}{\partial K2} dK2 + \frac{\partial J}{\partial G} dG$$

In Eq. (A-8), dK1 and dK2 represent changes in input parameters. Also, values for J and G can be calculated. The rest of the terms are given below.

$$\frac{\partial u}{\partial Q} = J \qquad \text{(A-9)}$$

and

$$dQ = dP \frac{\partial Q}{\partial P} = \left(\frac{10P}{210 + 2P} - \frac{10P^2}{(210 + 2P)^2} \right) dP \qquad \text{(A-10)}$$

where P is an input parameter. Further

$$\frac{\partial u}{\partial J} = Q \qquad \text{(A-11)}$$

and

$$\frac{\partial J}{\partial K1} = \frac{\dfrac{K2}{G^{1.5}}}{K1 + \dfrac{K2}{G^{1.5}}} - \frac{\dfrac{K1\ K2}{G^{1.5}}}{\left[K1 + \dfrac{K2}{G^{1.5}}\right]^2} \qquad \text{(A-12)}$$

$$\frac{\partial K}{\partial K2} = \frac{\left[K1 + \dfrac{K2}{G^{1.5}}\right] \dfrac{K1}{G^{1.5}} - \dfrac{K1\ K2}{G^{1.5}} \left(\dfrac{1}{G^{1.5}}\right)}{\left(K1 + \dfrac{K2}{G^{1.5}}\right)^2} \qquad \text{(A-13)}$$

$$\frac{\partial J}{\partial G} = \frac{\dfrac{1.5\ K1\ (K2)^2}{G^4}}{\left(K1 + \dfrac{K2}{G^{1.5}}\right)^2} - \frac{\dfrac{1.5\ (K1)\ K2}{G^{2.5}}}{\left(K1 + \dfrac{K2}{G^{1.5}}\right)} \tag{A-14}$$

This leaves only the term dG/G which will be developed later. The expression for the second term in Eq. (A-7), dM/M, will now be developed.

$$\frac{dM}{M} = \left(\frac{\partial M}{\partial G}\frac{dG}{M} + \frac{\partial M}{\partial HB}\frac{dHB}{M} + \frac{\partial M}{\partial WC}\frac{dWC}{M} + \frac{\partial M}{\partial Fy}\frac{dFy}{M} + \frac{\partial M}{\partial WBF}\frac{dWBF}{M} + \frac{\partial M}{\partial DC}\frac{dDC}{M}\right) \tag{A-15}$$

where

$$M = \frac{12G\ (HB)\ WC\ (FY)\ WBF}{DC^3} \tag{A-16}$$

The term dHB is a change in an input parameter so that the rest of the terms must be expanded. The development of terms $\partial M/\partial G$, $\partial M/\partial HB$, $\partial M/\partial WC$, $\partial M/\partial Fy$, $\partial M/\partial WBF$, and $\partial M/\partial DC$ is trivial and will not be shown.

$$WC = \frac{A1\ (DC)^{B1}}{HC}$$

$$dWC = \frac{\partial WC}{\partial A1}\,dA1 + \frac{\partial WC}{\partial B1}\,dB1 + \frac{\partial WC}{\partial DC}\,dDC + \frac{\partial WC}{\partial HC}\,dHC \tag{A-17}$$

$$= \frac{DC^{B1}}{HC}\,dA1 + \frac{A1\ (DC)^{B1}}{HC}(\ln\ DC)dB1 + \frac{B1\ (A1)(DC)^{B1-1}}{HC}\,dDC - \frac{A1\ (DC)^{B1}}{HC^2}\,dHC \tag{A-18}$$

$$= \frac{DC^{B1}}{HC} \left[dA1 + A1\ (\ln DC)\ dB1 + \frac{B1\ (A1)}{DC}\ dB1 - \frac{A1}{HC}\ dHC \right] \quad \text{(A-19)}$$

where terms dHC and dDC must be evaluated.

$$HC = AHB\ (HB) + AHB\ (4.5) - BHB \quad \text{(A-20)}$$

$$dHC = (HB + 4.5)\ dAHB - dBHB + AHBdHB \quad \text{(A-21)}$$

$$DC = \frac{DB\ (FC)}{A\ (FC + B)} \quad \text{(A-22)}$$

$$dDC = \frac{FC}{A\ (FC + B)} \left[dDB - \frac{DBdA}{A} - \frac{DBdB}{FC + B} \right] + \frac{DB}{A\ (FC + B)} \left[1 - \frac{FC}{FC + B} \right] dFC \quad \text{(A-23)}$$

$$FC = \frac{HC}{HB} = \frac{AHB\ (HB + 4.5) - BHB}{HB}$$

$$\text{(A-24)}$$

$$dFC = \frac{(4.5 + HB)}{HB}\ dAHB - \frac{dBHB}{HB} - \left[\frac{4.5\ AHB - BHB}{HB^2} \right] dHB$$

The next term in Eq. (A-15) to be expanded is the term dFy where

$$Fy = FC - FP = \frac{HC - HP}{HB} \quad \text{(A-25)}$$

$$dFY = \frac{dHC}{HB} - \frac{dHP}{HB} - \frac{dHB}{HB^2} \quad \text{(A-26)}$$

In Eq. (A-26) dHC is given by Eq. (A-21) and dHP will be determined later as the expression for HP is different for conifers and broadleafs. Returning to Eq. (A-15):

$$WBF = A2\ (DC)^{B2}$$

$$dWBF = DC^{B2}\ dA2 + A2\ (DC)^{B2}\ (\ln DC)\ dB2 + B2\ (A2)(DC)^{B2-1} \tag{A-27}$$

$$= A2\ (DC)^{B2} \left[\frac{dA2}{A2} + \ln DC\ dB2 + \frac{B2\ dDC}{DC}\right] \tag{A-28}$$

where dDC is given in Eq. (A-23) and dA2 and dB2 are changes in input parameters. Thus all terms of equation have been determined in terms of input parameters except for dG/G and dHP.

Turning now to Eq. (A-5) for x, it was found that

$$x = \frac{0.23Q\ (T)\ J}{IQ\ (K1)}$$

using the form dz/z, where z = u/v;

$$\frac{dz}{z} = \frac{du}{u} - \frac{dv}{v} \tag{A-29}$$

$$\frac{dx}{x} = \frac{d\ (0.23\ QJT}{0.23\ Q\ (J)\ T} - \frac{d\ (K1\ IQ)}{K1\ (IQ)} \tag{A-30}$$

where

$$u = 0.23Q\ (J)\ T$$

and

$$v = K1\ (IQ)$$

$$\frac{du}{u} = \frac{\partial u}{\partial Q}\frac{dQ}{u} + \frac{\partial u}{\partial J}\frac{dJ}{u} + \frac{\partial u}{\partial T}\frac{dT}{u} \tag{A-31}$$

Determining dQ, dJ, and dT and substituting into Eq. (A-31) yields:

$$\frac{du}{u} = \frac{d\ (0.23QJT)}{0.23QJT} = \frac{\partial u}{\partial Q}\frac{\partial Q}{\partial P}\frac{dP}{u} + \frac{\partial u}{\partial J}\left[\frac{\partial J}{\partial K1}\,dK1 + \frac{\partial J}{\partial K2}\,dK2 + \frac{\partial J}{\partial G}\,dG\right]\frac{1}{u}$$

$$+ \frac{\partial u}{\partial T}\left[\frac{\partial T}{\partial A3}\,dA3 + \frac{\partial T}{\partial B3}\,dB3 + \frac{\partial T}{\partial HB}\,dHB + \frac{\partial T}{\partial DB}\,dDB\right]\frac{1}{u} \qquad \text{(A-32)}$$

where

$$\frac{\partial u}{\partial Q}\cdot\frac{\partial Q}{\partial P}\cdot\frac{dP}{u} = \left(\frac{P}{2} - \frac{2}{210 + 2P}\right)dP \qquad \text{(A-33)}$$

$$\frac{\partial u}{\partial J}\cdot\frac{\partial J}{\partial K1}\cdot\frac{dK1}{u} = \left(\frac{1}{K1} - \frac{1}{K1 + \frac{K2}{G^{1.5}}}\right)dK1 \qquad \text{(A-34)}$$

$$\frac{\partial u}{\partial J}\cdot\frac{\partial J}{\partial K2}\cdot\frac{dK2}{u} = \left(\frac{1}{K2} - \frac{1/G^{1.5}}{K1 + \frac{K2}{G^{1.5}}}\right)dK2 \qquad \text{(A-35)}$$

$$\frac{\partial u}{\partial J}\cdot\frac{\partial J}{\partial G}\cdot\frac{dG}{u} = \left[\frac{\frac{1.5\ K2}{G^{2.5}}}{\frac{K1}{G} + \frac{K2}{G^{2.5}}} - 1.5\right]\frac{dG}{G} \qquad \text{(A-36)}$$

$$\frac{\partial u}{\partial T}\cdot\frac{\partial T}{\partial A3}\cdot\frac{dA3}{u} = \frac{dA3}{T} \qquad \text{(A-37)}$$

$$\frac{\partial u}{\partial T}\cdot\frac{\partial T}{\partial B3}\cdot\frac{dB3}{u} = \left[\frac{1}{\frac{A3\ (DB)}{HB^2} + B3}\right]dB3 \qquad \text{(A-38)}$$

$$\frac{\partial u}{\partial T}\cdot\frac{\partial T}{\partial HB}\cdot\frac{dHB}{u} = \left[\frac{2\ (B3)\ HB}{A3\ (DB) + B3\ (HB)^2}\right]dHB \qquad \text{(A-39)}$$

$$\frac{\partial u}{\partial T} \cdot \frac{\partial T}{\partial DB} \cdot \frac{dDB}{u} = \left[- \frac{B3\ (HB)^2}{A3\ (DB)^2 + B3\ (DB)(HB)^2} \right] dDB \qquad \text{(A-40)}$$

All quantities in Eqs. (A-33) to (A-40) can be evaluated except for dG/G. Returning to Eq. (A-30):

$$v = K1\ (IQ)$$

$$\frac{dv}{v} = \frac{\partial v}{\partial K1} \frac{dK1}{K1} + \frac{\partial v}{\partial IQ} \left[\frac{\partial IQ}{\partial P} dP + \frac{\partial IQ}{\partial W} dW \right] \frac{1}{IQ} \qquad \text{(A-41)}$$

which becomes

$$\frac{d\ (K1\ IQ)}{K1\ IQ} = \frac{IQ}{K1} dK1 + K1 \left[\frac{2}{P} - \frac{11}{6\ (20.6 + P)} \right] dP + \frac{K1}{3W} dW \qquad \text{(A-42)}$$

The remaining quantities which must be expressed in terms of input parameters are dG/G and dHP.

$$G = \frac{\pi\ (DI)^3\ SR}{384\ (HB)(FX)(SMB)(WC)} \qquad \text{(A-43)}$$

where

$$FX = 1 - FP$$

Using the usual techniques

$$\frac{dG}{G} = \left[\frac{3\ dDI}{DI} + \frac{dSR}{SR} - \frac{dHB}{HB} - \frac{dFX}{FX} - \frac{dSMB}{SMB} - \frac{dWC}{WC} \right] \qquad \text{(A-44)}$$

where SR and HB are input parameters, dWC is given by Eq. (A-18), and dDI, dFX, and dSMB must be found in terms of input parameters.

$$DI = \frac{DB}{A\ (1 + B)} \tag{A-45}$$

$$\frac{dDI}{DI} = \frac{dDB}{DB} - \frac{dA}{A} - \frac{dB}{(1 + B)} \tag{A-46}$$

$$FX = 1 - FP = 1 - \frac{HP}{HB} \tag{A-47}$$

$$dFX = \frac{HP}{HB^2}\, dHB - \frac{dHP}{HB} \tag{A-48}$$

$$SMB = \frac{FM - FP}{1 - FP} \left[\frac{FM + B}{FM\ (1 + B)}\right]^3 \tag{A-49}$$

where

$$FM = B \left[1 - \left(1 - \frac{3\ FP}{B}\right)^{1/2}\right] \tag{A-50}$$

and

$$FP = \frac{HP}{HB} \tag{A-51}$$

$$dSMB = \frac{\partial SMB}{\partial FM}\, dFM + \frac{\partial SMB}{\partial FP}\, dFP \quad \frac{\partial SMB}{\partial B}\, dB \tag{A-52}$$

where B is an input parameter and dFP is given by

$$dFP = \frac{dHP}{HB} - \frac{HP}{HB^2}\, dHB \tag{A-53}$$

and dFM by:

$$dFM = \left[1 - \frac{2 - \frac{3FP}{B}}{\left(1 - \frac{3FP}{B}\right)^{1/2}}\right] dB - \frac{1.5}{\left(1 - \frac{3FP}{B}\right)^{1/2}} \left[\frac{dHP}{HB} - \frac{HP}{HB^2}\, dHB\right] \qquad \text{(A-54)}$$

and

$$\frac{\partial SMB}{\partial FM} = \frac{B\ (FM + B)^2}{FM\ (1 - FP)[FM\ (1 + B)]^3} \left(3\ FP - 2\ FM + \frac{(FM)^2}{B}\right) \qquad \text{(A-55)}$$

$$\frac{\partial SMB}{\partial FP} = \left[\frac{FM + B}{FM\ (1 + B)}\right]^3 \left[\frac{FM - FP}{(1 - FP)^2} - \frac{1}{(1 - FP)}\right] \qquad \text{(A-56)}$$

$$\frac{\partial SMB}{\partial B} = 3 \left[\frac{FM - FP}{1 - FP}\right] \frac{(FM + B)^2}{[FM\ (1 + B)]^3} \left[1 - \frac{FM + B}{1 + B}\right] \qquad \text{(A-57)}$$

which leaves only dHP to be determined.

For conifer trees

$$HP = 1.3\ DC + 0.1\ HC\ (WBF) \qquad \text{(A-58)}$$

$$dHP = 1.3\ dDC + 0.1\ (WBF)\ dHC + 0.1\ (HC)\ dWBF \qquad \text{(A-59)}$$

where dDC is given by Eq. (A-23), dHC by Eq. (A-21) and dWBF by Eq. (A-28).

For broad leaf trees, HP is found from a third degree polynomial fit to the data where

$$HP = HC\left(a + bx + Cx^2 + dx^3\right) \qquad \text{(A-60)}$$

where a, b, c, and d are constant coefficients of the terms and

$$x = \frac{DC\ (HB)}{DB} \tag{A-61}$$

$$dhp = \frac{\partial HP}{\partial HC}\, dHC + \frac{\partial HP}{\partial HB}\, dHB + \frac{\partial HP}{\partial DC}\, dDC + \frac{\partial HP}{\partial B}\, dDB \tag{A-62}$$

where dHB and dDB are changes in input variables, and dHC and dDC are known. Determining the remainder of the terms and rearranging yields

$$\begin{aligned} dHP = HC \Bigg\{ & \frac{adHC}{HC} + \frac{b\ (HB)\ DC}{DB} \left[\frac{dHC}{HC} + \frac{dHB}{HB} + \frac{dDC}{DC} - \frac{dDB}{DB}\right] \\ & + c \left[\frac{(HB)\ DC}{DB}\right]^2 \left[\frac{dHC}{HC} + \frac{2\ dHB}{HB} + \frac{2\ dDC}{DC} - \frac{2\ dDB}{DB}\right] \\ & + d \left[\frac{(HB)\ DC}{DB}\right]^3 \left[\frac{dHC}{HC} + \frac{3\ dHB}{HB} + \frac{3\ dDC}{DC} - \frac{3\ dDB}{DB}\right] \end{aligned} \tag{A-63}$$

where a = +0.98865857

b = -0.17016963

c = +0.009271084

d = -0.00013239524

Also for the broad leaf case the term WBF is equal to 1.00, and therefore dWBF = 0.

Appendix B

AIRBLAST EFFECTS

15.1 AIRBLAST EFFECTS

15.1.1 General Description. The effects of a nuclear detonation on a forest may have a significant influence on military operations within the affected region of the forest. Historically, forests have been used to military advantage because of the cover and concealment they may offer. Forests may also serve to impede or channel military operations.

Two HE tests have been held from which extensive information has been obtained concerning the character of the damaged region and the effect on vehicular and troop movement. The general descriptions of the area damaged by these two detonations have been scaled to 1 KT nuclear and are given in Tables 15-1 and 15-2, from Ref. 10. The damage described in Table 15-1 resulted from a 60-ton TNT detonation over a rain forest. Table 15-2 describes the damage resulting from a 50-ton TNT surface burst in a coniferous forest. The differences in ground range for similar damage, i.e., 50 percent of trees down, is believed to be caused primarily by the greater strength of the broadleaf trees and their greater diameter. These differences tend to offset the effects of increasing the height of burst and using higher yields, which tend to increase the range of effects. One important difference between the effects on broadleaf and coniferous forests is the nature of the debris. Because of the difference in tree types, branch debris is much more in evidence for the broadleaf forest. Also broadleaf trees have a greater tendency to fail through stem breakage rather than uprooting. In the coniferous forest described, approximately 85 percent of the trees failed by uprooting. This percentage is not expected to be as high for coniferous forests in general because growing conditions are expected to be better. However, the differences between the blowdown debris characteristics for broadleaf and coniferous forests produce significantly different impacts on troop and vehicular movement.

Growing conditions for trees have an influence on how trees fail under blast loading. When a tree fails through stem breakage, the stem is more often than not supported on its branches. However, a large number of trees felled in a similar manner tend to become somewhat compacted. When trees fail through uprooting, one end of the stem is supported above ground by the root ball, reducing the tendency to compact. This creates a somewhat more difficult obstacle to movement and debris clearance. Under good growing conditions, about half the trees fail by uprooting. Eighty to ninety percent fail by uprooting for sites with poor growing conditions.

15.1.2 Predicting Blowdown Damage. Certain data is required in order to predict the ground range at which certain damage levels will occur for particular forests, yields, and heights-of-burst. The forest data generally required are 1) the forest type and class, 2) the average height of the forest, and 3) the site conditions. There are three general forest types: conifer, broadleaf, and defoliated broadleaf. The forest classes generally refer to light crowned trees for Class I, and heavy crowned trees for Class II. The detailed descriptions of the forest types and classes are given below.

Conifer

Class I - light crowned conifer trees consisting of such trees as spruces, cedars, hemlocks, and larches. Needle length generally less than 2-1/2 in., medium shade tolerance, and needle persistance on the order of 3 years.

Class II - heavy crowned conifer trees consisting of mostly pines and firs. Needle length generally greater than 2-1/2 in., with less shade tolerance than Class I conifers, and needle persistance averaging 5 years.

Broadleaf

Class I - characterized by trees with generally small leaves or light crowns such as birches, poplars, and scarlet oak.

Class II - characterized by trees with generally large leaves or heavy crowns such as beeches, hickory, maples, and sycamores.

Defoliated Broadleaf - All broadleafs in a defoliated condition.

Site conditions generally refer to conditions of growth and are related to factors of rainfall, soil depth and suitability, latitude, and elevation. The detailed descriptions of site conditions are given below.

Good Site - characterized by well-drained soil layer that is deep and generally free of rocks. Adequate precipitation is available with temperatures favorable for a long growing season. Generally north-facing slopes, valley, and well-drained flats are good locations in the middle elevations and latitudes.

Poor Site - characterized by wet or poorly drained soil and/or shallow soil with a large amount of rocks or silt content. Deficient annual rainfall, and a short growing season such as the higher altitudes, latitudes. Poor growing conditions can be characterized also by arid ridges, poorly drained flats, and steep south-facing slopes.

It should be noted that average forest height is not required to predict ground range for damage to broadleaf or defoliated broadleaf forests. This data is required together with forest density in trees per acre and average diameter of the trees in order to assess the effects of forest damage on movement.

The damage to forests is generally expressed in terms of the percentage of trees down. The specific definitions of damage levels are:

Light Damage - 10 percent of trees down. Little impediment to movement likely. For forests with large secondary growth, underbrush or vines, some improvement over virgin forest conditions possible due to improved visibility.

Moderate Damage - 50 percent of trees down. Significant effect on movement of troops, especially in units. Greater effect in damaged broadleaf forest because of greater amount of branch debris. Slowing of vehicles possib'e, particularly for forests of high density.

Severe Damage - 90 percent of trees down. Severe obstacle to troop movement in units or individually. Substantial probability of stopping wheeled vehicles, and slowing of tracked vehicles, depending on forest density.

Destroyed - Essentially all vegetation removed. No impediment to visibility or movement. Generally extends from GZ to 60 percent of the Severe Damage ground range.

The vegetation originally present in the destroyed area has been severely fractured. Some of the fragments have been consumed in the fireball, with the remainder transported by the shock wave and deposited throughout the region of shock wave effects.

The ground ranges to specific damage levels for particular forest types and classes are determined from Figs. 15-1 through 15-7. These figures indicate, for various forest types, forest heights, and site conditions, the probability of blowdown as a function of yield and overpressure. Three probabilities are plotted, 10%, 50%, and 90%. Other probabilities may be interpolated, but should not be extrapolated below 10% or above 90% A plot of ground range vs. percentage of trees down may be used for this purpose. The method of obtaining ground range predictions is described below. The figure for defoliated broadleaf is for average site conditions only. This is due to a scarcity of data for this forest type which prevents the discrimination between good and poor site conditions. Following are some examples of forest blowdown prediction.

The ground ranges to specific damage levels for particular forest types and classes are determined from Figs. 15-1 through 15-7. The figure for defoliated broadleaf is for average site conditions only. This is due to a scarcity of data for this forest type which prevents the discrimination between good and poor site conditions. Following are some examples of forest blowdown prediction.

Example 15-1

Given: A 250 KT burst at 1000 ft over a broadleaf, Class I forest with good site conditions.

Find: The ground ranges to Light, Moderate, Severe damage, and Destroyed zones

Solution: From Fig. 15-1, the overpressures for light, moderate, and severe damage are 8.5, 11.3, and 15 psi, respectively. The scaled HOB is:

$$SHOB = \frac{1000}{250^{1/3}}$$

$$= \frac{1000}{6.3}$$

$$= 158 \text{ ft}/w^{1/3}$$

From the overpressure HOB chart of Chapter 2, the scaled ground ranges to each overpressure level are 1170, 1035, and 870 ft for 8.5, 11.3, and 15 psi. Converting to ground ranges for 250 KT:

$$1170(250)^{1/3} = 7370 \text{ ft, light damage}$$

$$1035(250)^{1/3} = 6520 \text{ ft, moderate damage}$$

$$870(250)^{1/3} = 5480 \text{ ft, severe damage}$$

As the destroyed zone extends out to a ground range equal to 60 percent of the ground range for severe damage, the limit of the destroyed zone is 3290 ft.

Example 15-2

Given: A 27 KT burst at 300 ft over a conifer, Class II forest. The forest has an average height of 100 ft and good site conditions.

Find: The ground range to severe damage.

Solution: Interpolation between the 80 and 120 ft forest height curves of Fig. 15-6 is necessary. The overpressures for 80 ft and 120 ft are 4.2 and 5.2 psi, respectively. Interpolating gives:

$$OP = 4.2 + \left(\frac{100-80}{120-80}\right)(5.2 - 4.2)$$

$$= 4.2 + 0.5(1)$$

$$= 4.7 \text{ psi}$$

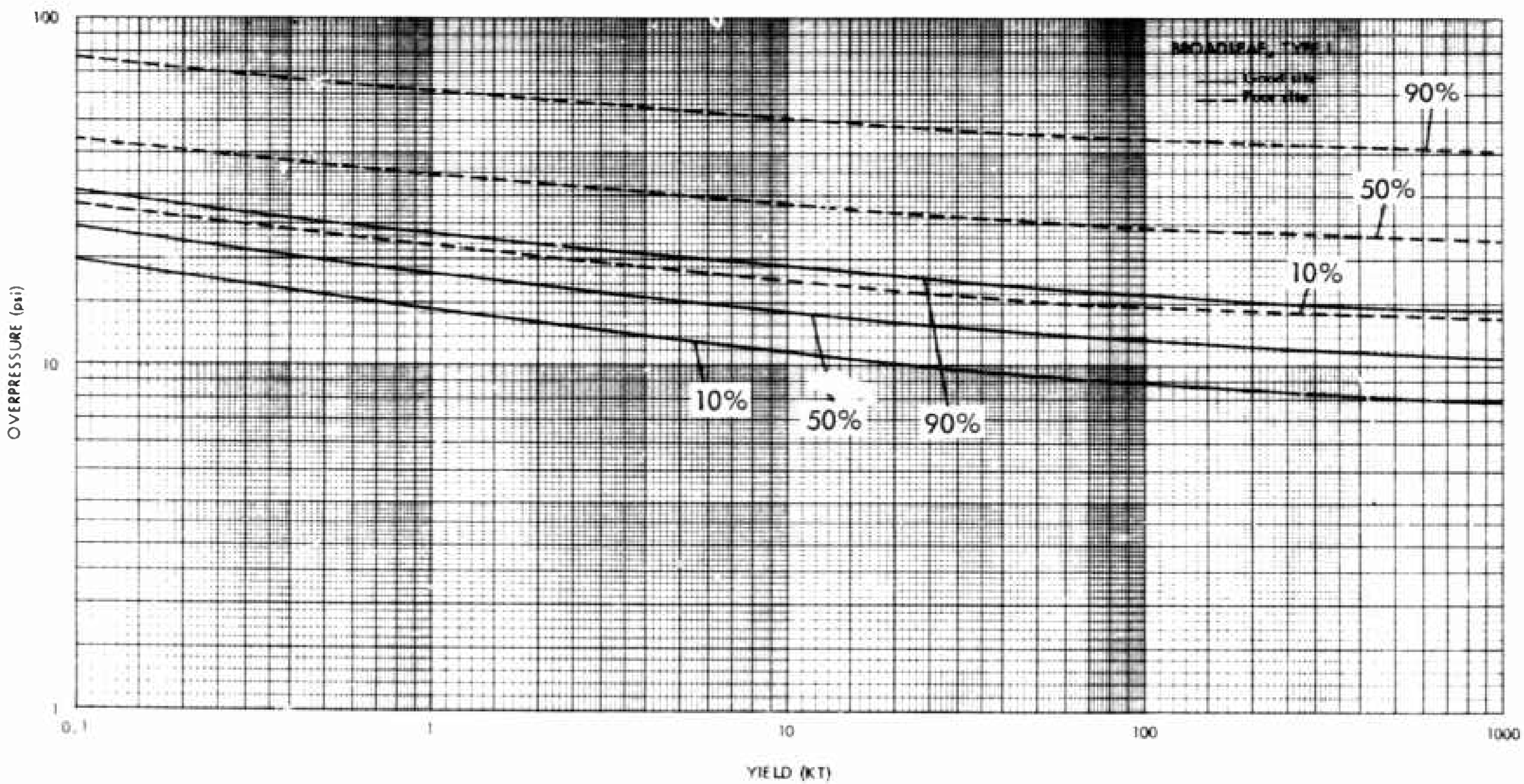

Fig. 15-1. Probability of Blowdown vs Yield and Overpressure, Broadleaf, Type I Forests

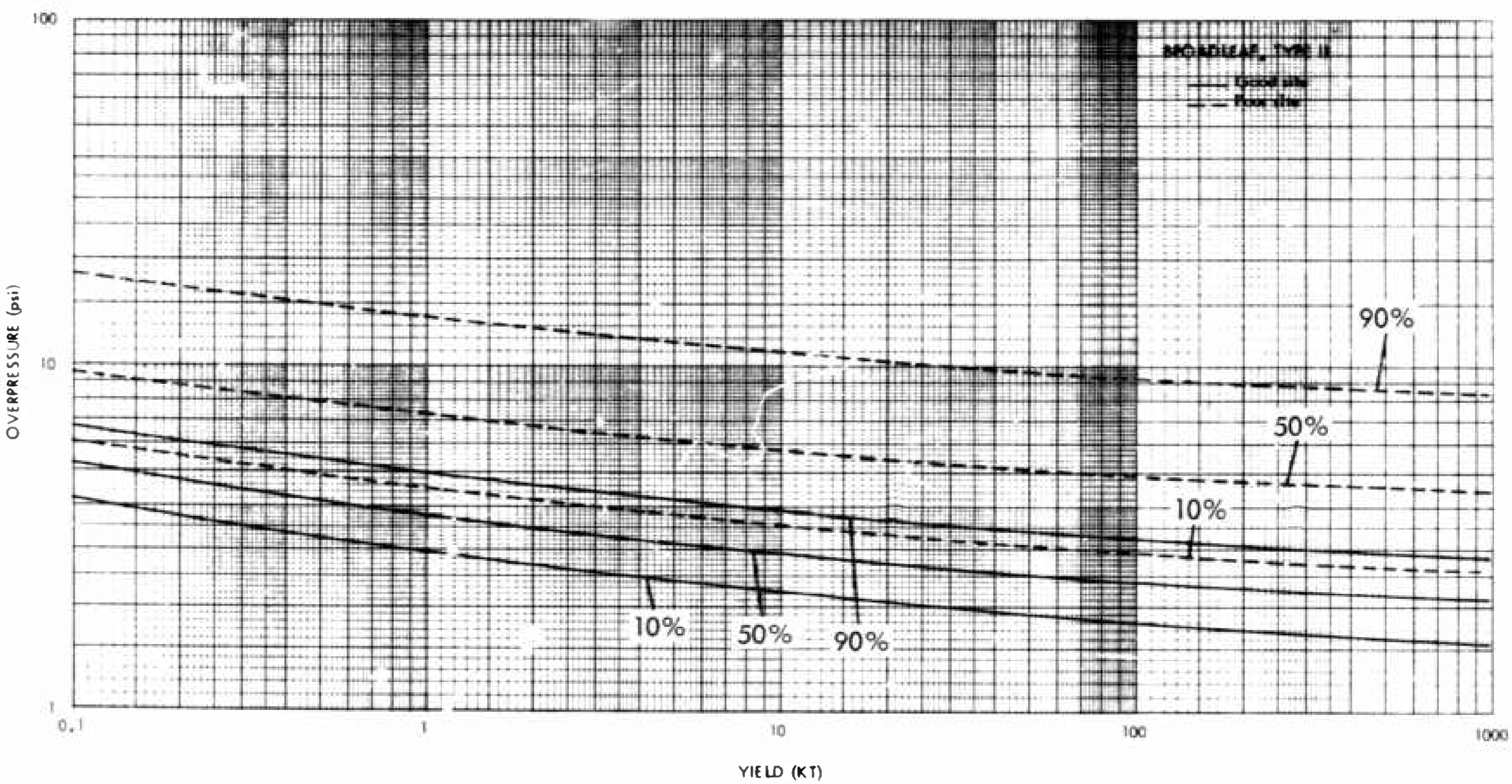

Fig. 15-2. Probability of Blowdown vs Yield and Overpressure, Broadleaf, Type II Forests

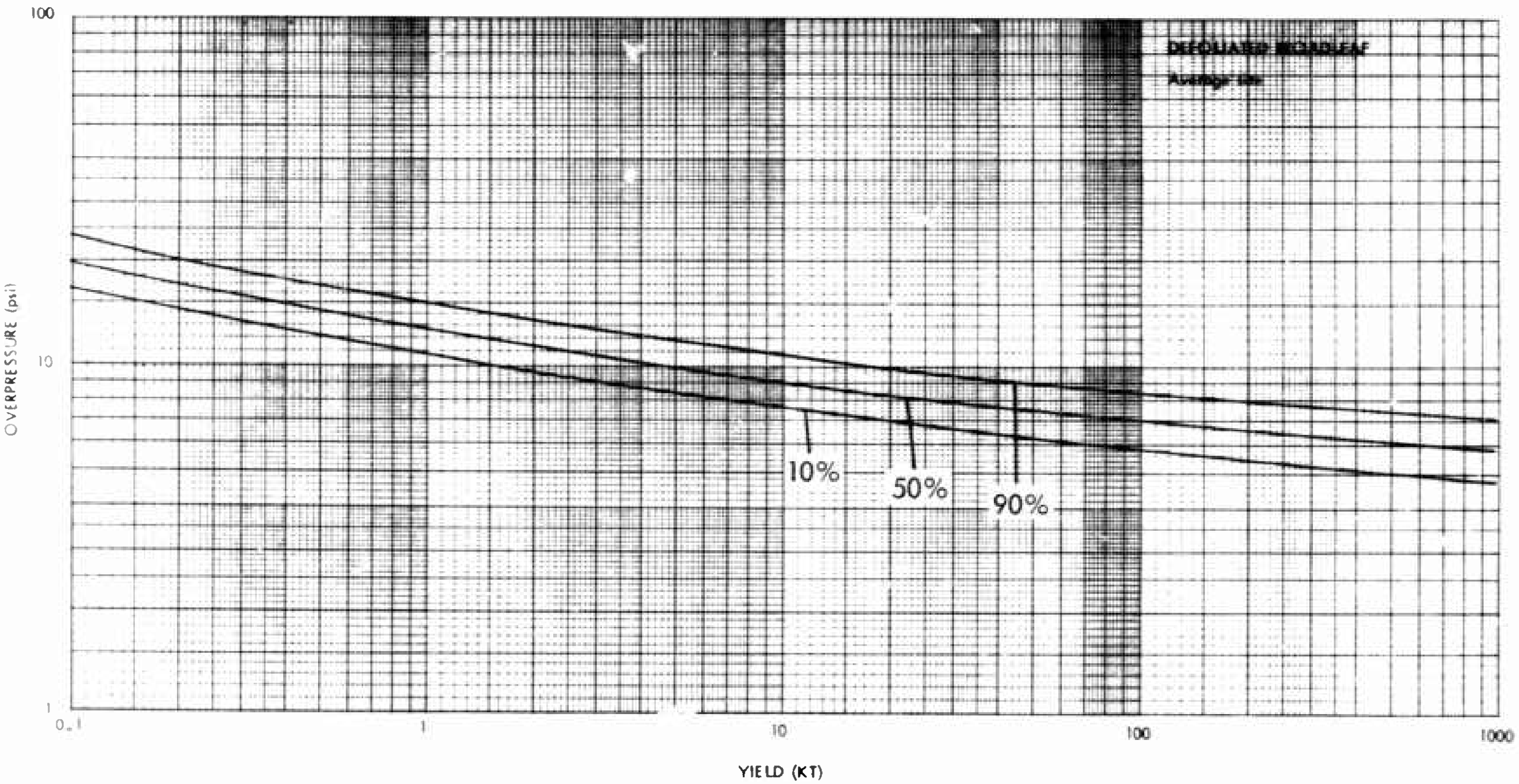

Fig. 15-3. Probability of Blowdown vs Yield and Overpressure, Defoliated Broadleaf Forests

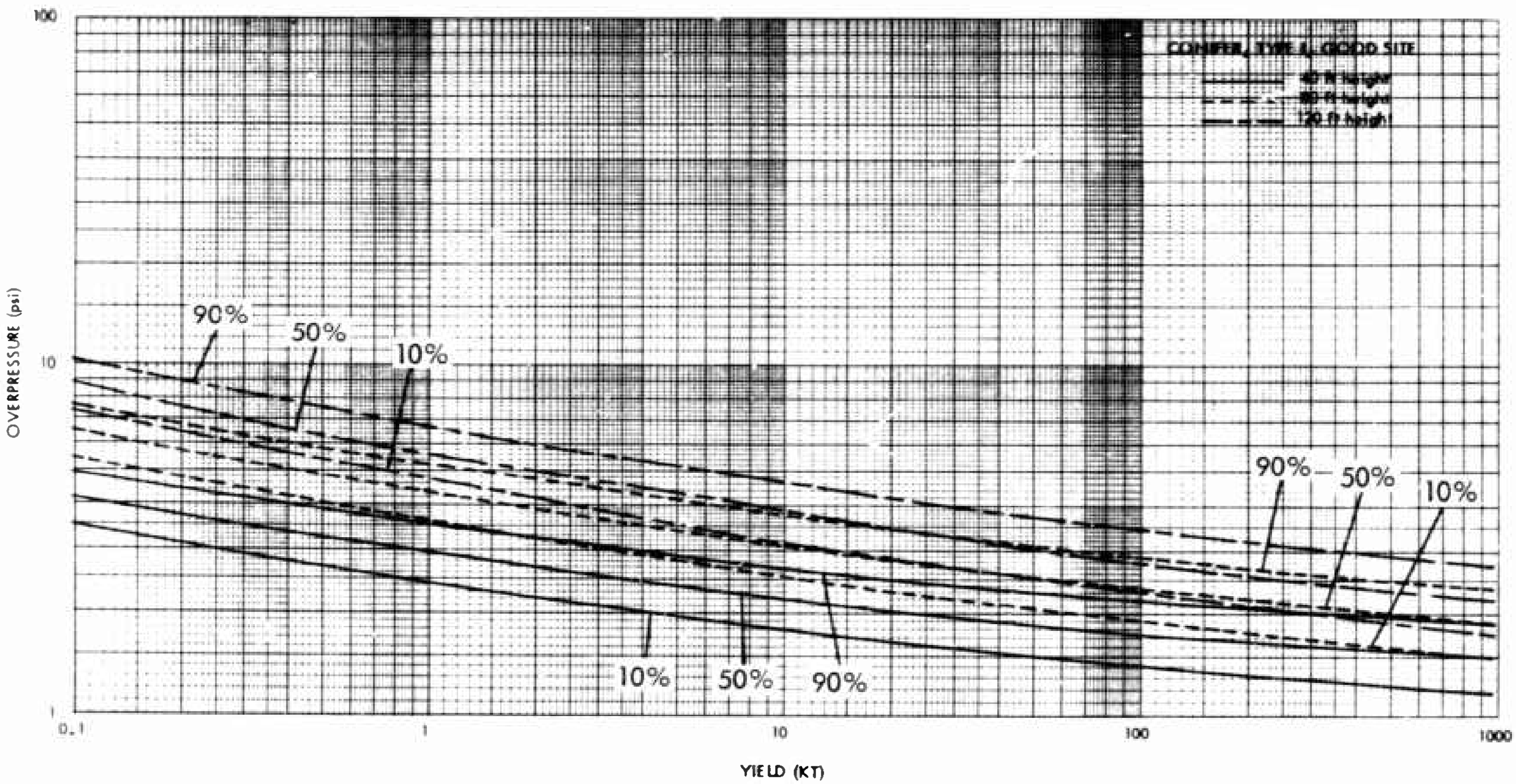

Fig. 15-4. Probability of Blowdown vs Yield and Overpressure, Conifer, Type I Forests, Good Site

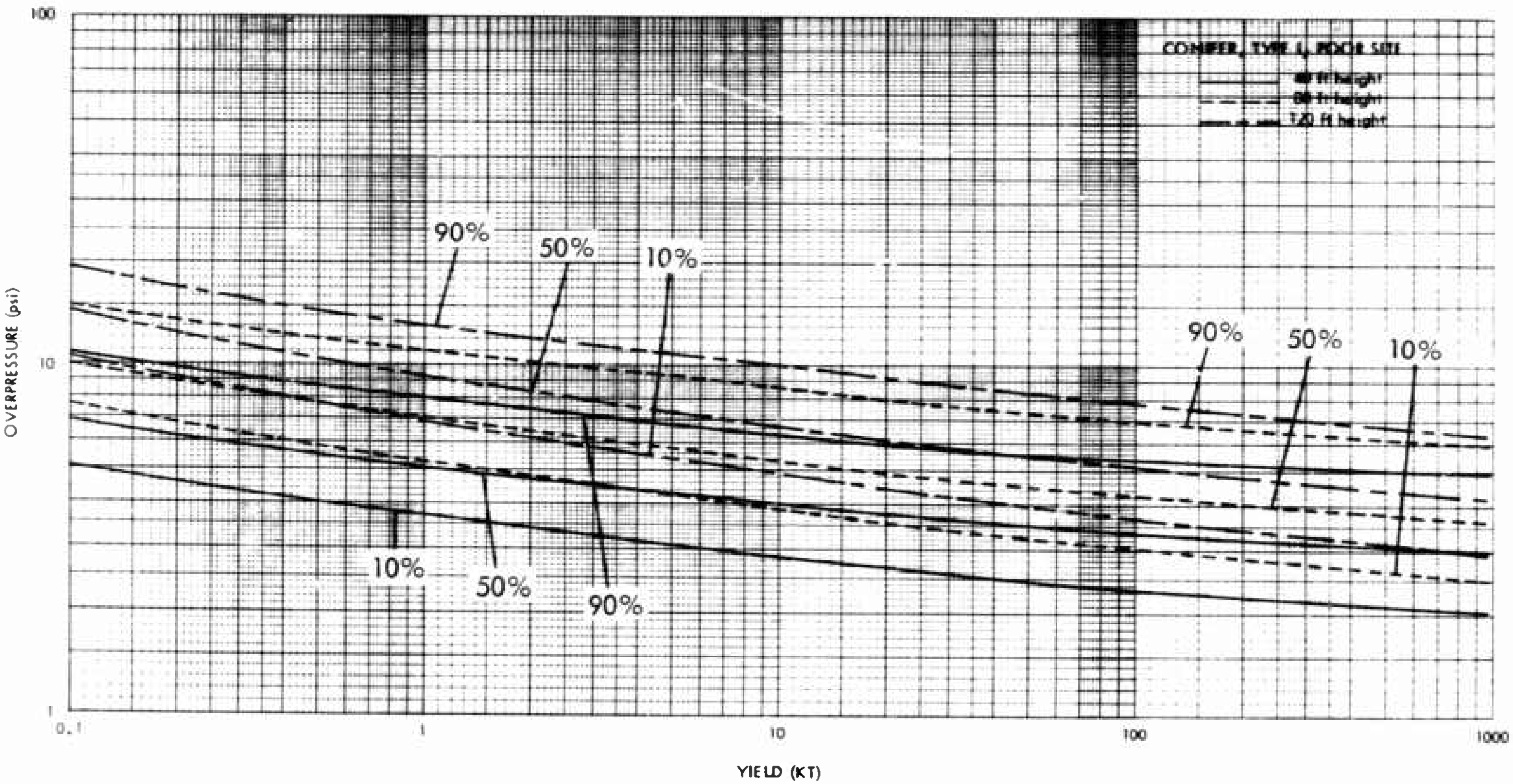

Fig. 15-5. Probability of Blowdown vs Yield and Overpressure, Conifer, Type I Forests, Poor Site

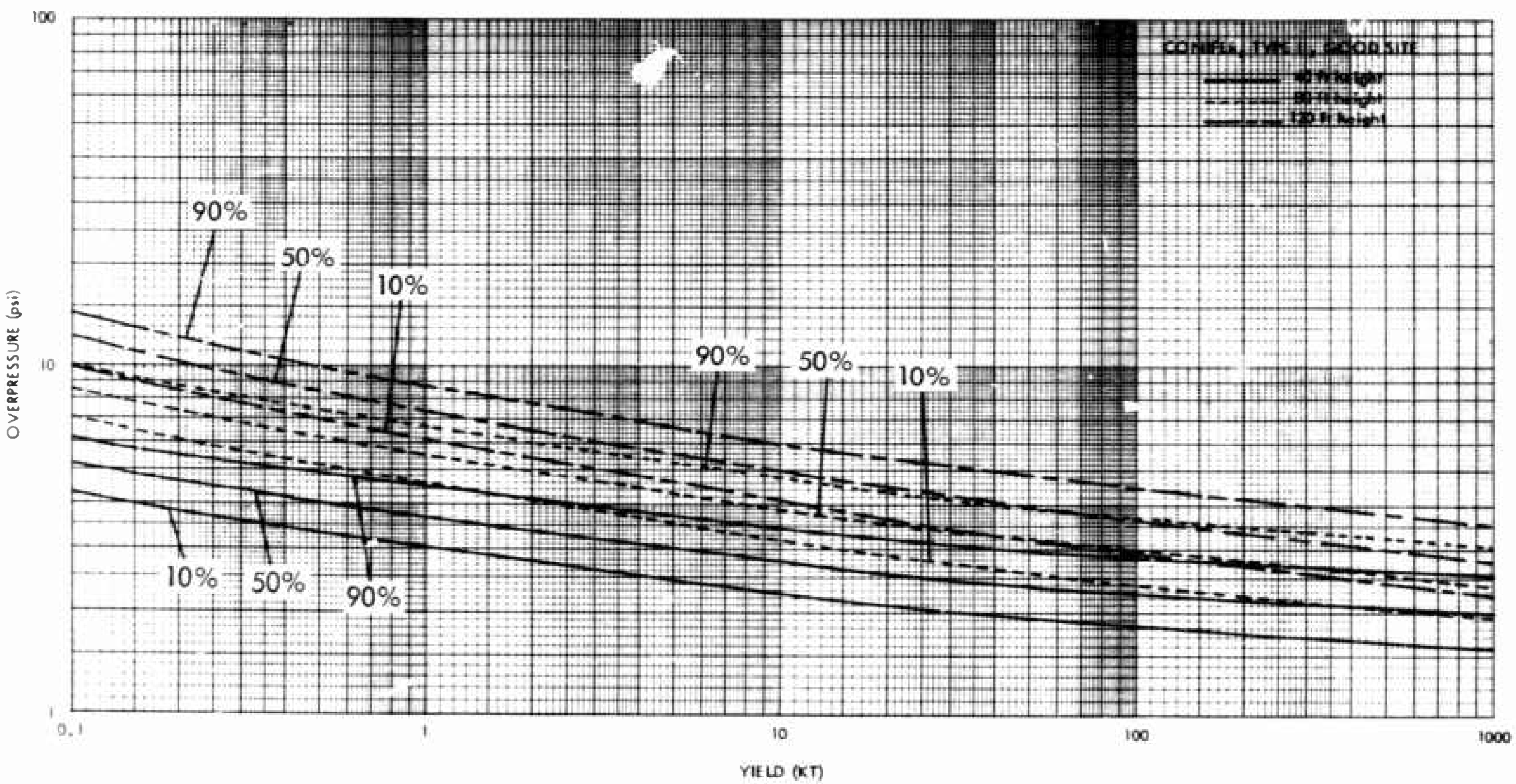

Fig. 15-6. Probability of Blowdown vs Yield and Overpressure, Conifer, Type II Forests, Good Site

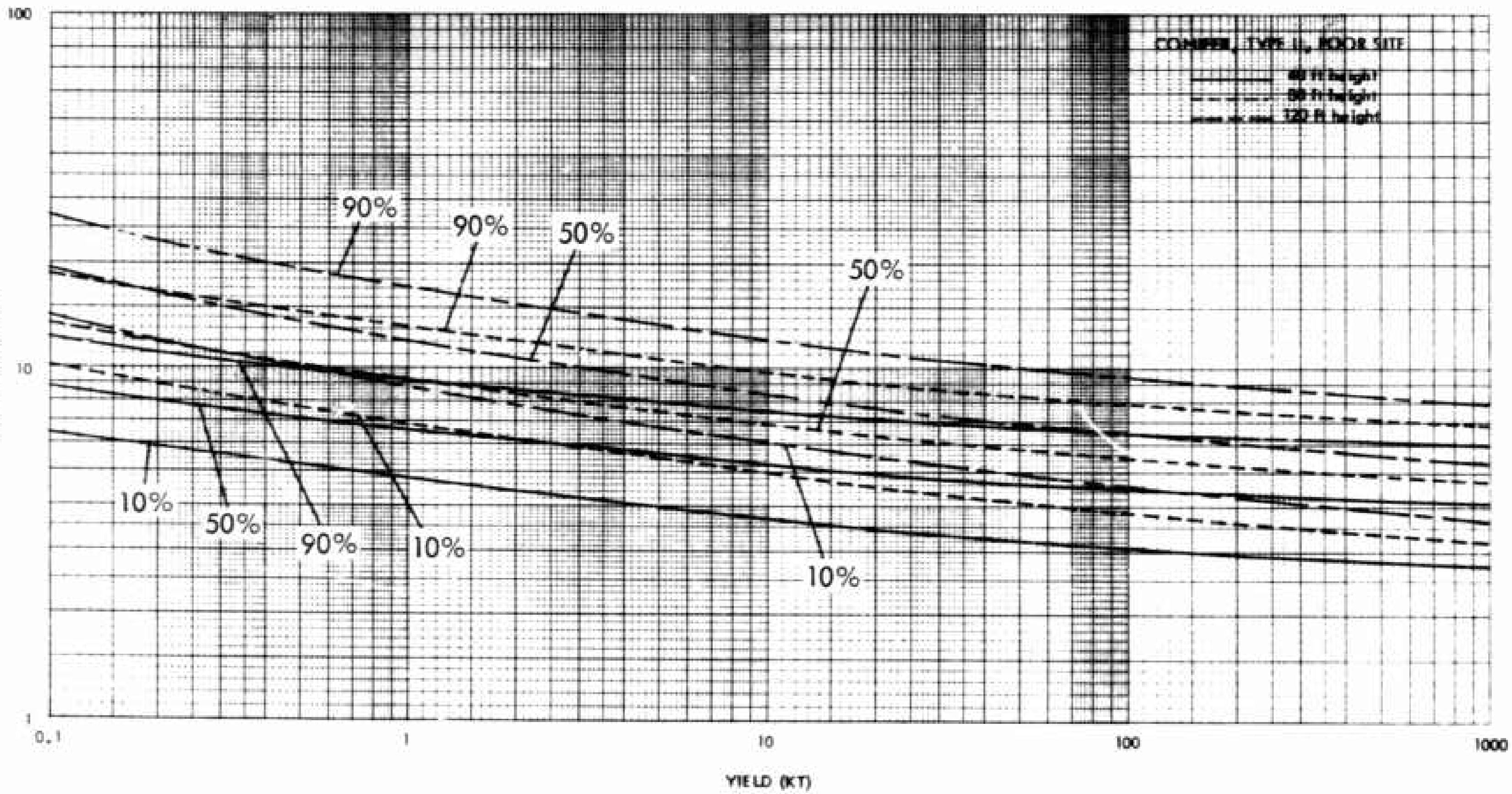

Fig. 15-7. Probability of Blowdown vs Yield and Overpressure, Conifer, Type II Forests, Poor Site

The scaled HOB is:

$$SHOB = \frac{300}{27^{1/3}} = 100 \text{ ft}$$

From the overpressure HOB charts of Chapter 2, the scaled ground range to 4.7 psi is 1630 ft. The actual ground range is $1630(27)^{1/3} = 4890$ ft for severe damage.

15.1.3 Blowdown Debris Characteristics. The impact of the damaged region of a forest on movement of troops and vehicles is determined from the number and diameter of stems in the path of the vehicle or troops. This section will present what is known about the variation in these parameters throughout various regions of damage.

Data from the two detonation previously discussed are presented in Figs. 15-8 and 15-9. Figure 15-8 presents the relationship between debris in stem-feet per acre and ground range for a rain forest and for a coniferous forest. Stem size is for diameters greater than 2 in. (5 cm). The differ- in maximum debris in stem-feet per acre between the two forests is due to the difference in average tree density and tree height of each forest.*

* Stem-feet per acre is determined by multiplying average tree height by tree density. A forest having 50-ft average height and 200 trees per acre has (50)(200) = 10,000 stem-feet per acre.

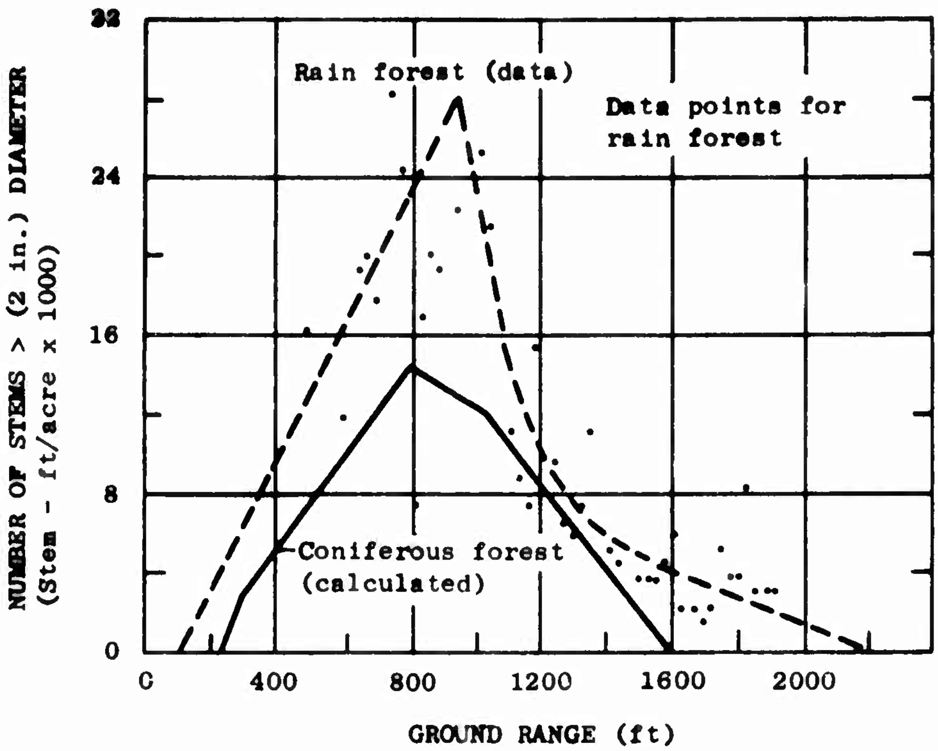

Fig. 15-8. Stem-ft per Acre Comparison Between a Rain Forest and a Coniferous Forest

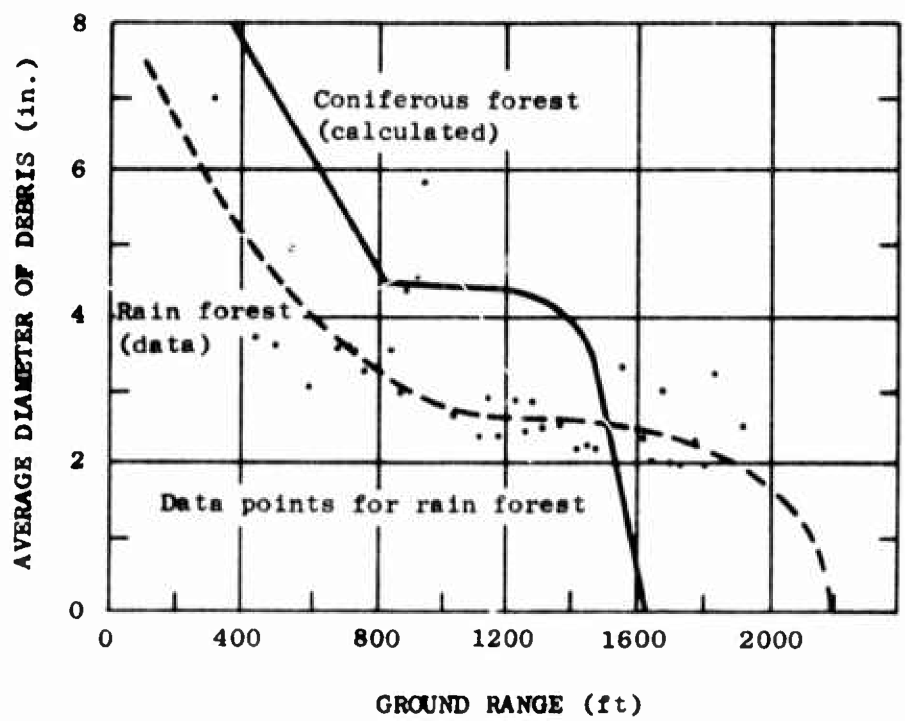

Fig. 15-9. Average Diameter of Stems Down, Comparison Between a Rain Forest and a Coniferous Forest, 1 KT

The curve for the rain forest is based on data gathered through observation, and the curve for the coniferous forest is based on calculations using preshot and postshot tree surveys. Figure 15-9 presents the relationship between ground range and average diameter of the debris. The diameter at 820 ft (250 m) for the coniferous forest is about the average diameter expected because at this ground range nearly all trees are down in place. The debris survey data for the rain forest, however, comprises all debris, including branches. Thus, the rain forest debris has a lower average diameter than that of the trees, which is about 25-28 in. (10 to 11 cm). This illustrates further that branch debris is much more in evidence and important for broadleaf forests than for coniferous forests. Further support for this statement is given by the observation that debris in the rain forest extends significantly beyond the range at which most trees remain standing. For the coniferous forest, the ratio of the ground range for no debris to ground range for 90 percent of trees standing is 1.12; and for the broadleaf forest, this ratio is 1.59. The apparent explanation for this observation is that beyond the ranges where little broadleaf tree stem failure occurs, branch failure continues. This factor may be significant for troop movement.

The average diameter of the trees in a forest is determined from the average of diameters at breast height or 4.5 ft (1.4 m). Thus the true average diameter of the trees is equal to the diameter at one-half the stem length. The average diameter at breast height, d_{bh}, is the usual way of describing a forest stand, and some calculation is required to obtain the debris diameter parameters to assess effects on movement. The debris diameter parameter required is the average debris diameter, d_a. For conifer forests, the majority of the debris is made up of stems and the average debris diameter can be found from

$$d_a = \frac{5d_{bh}}{7 - \frac{18}{H}} \qquad (15.1)$$

where H is the average height of the forest in feet, and d_{bh} is the average diameter at breast height in inches. The debris from broadleaf forests is made up of a significant portion of branches and the average debris diameter can be found from

$$d_a = \frac{d_{bh}}{2 - \frac{6}{H}} \tag{15.2}$$

One further item of interest should be noted, and it will be shown later to be of assistance in assessing obstacles to movement of troops and vehicles. The peak values of stem-feet down per acre and average diameter of standing tree stems both occur at ground ranges essentially equal to the ground ranges for 90 percent of trees down for both forests. The latter ground range is easily determined from photo reconnaissance, as are the debris zones described in Tables 15-1 and 15-2.

15.1.4 <u>Vehicle Movement.</u> The rates of movement or speeds of various wheeled and tracked vehicles have been measured for both radial and circumferential traverses of various debris zones. Although quantitative data were obtained and can be utilized, correlations between vehicle movement and debris characteristics are incomplete and not refined to the point of high reliability. Nevertheless, curves have been constructed which indicate in terms of the debris parameters (number of stem-feet per acre and diameter of debris) when a vehicle will not be able to move. These curves are presented in Figs. 15-10 and 15-11. The curves are for two types of movement, radial from GZ and circumferential. The general radial orientation of tree stems is significant in terms of movement because selection of easier routes between stems is possible in some cases, instead of having to cross all stems as in circumferential movement. The cross-hatched areas on the graphs indicate debris characteristics where movement is difficult, with the solid line indicating no movement. For example, in Fig. 15-11, for wheeled vehicles and debris characteristics of 10,000 stem-ft per acre with average diameters of 4, 6, and 8 in. (10, 15 and 20 cm), radial movement would be possible, difficult, and not possible, respectively. Curves for wheeled vehicles are fairly well documented with data; however, the curves for the M113 and tank are not because these vehicles were slowed but not stopped by

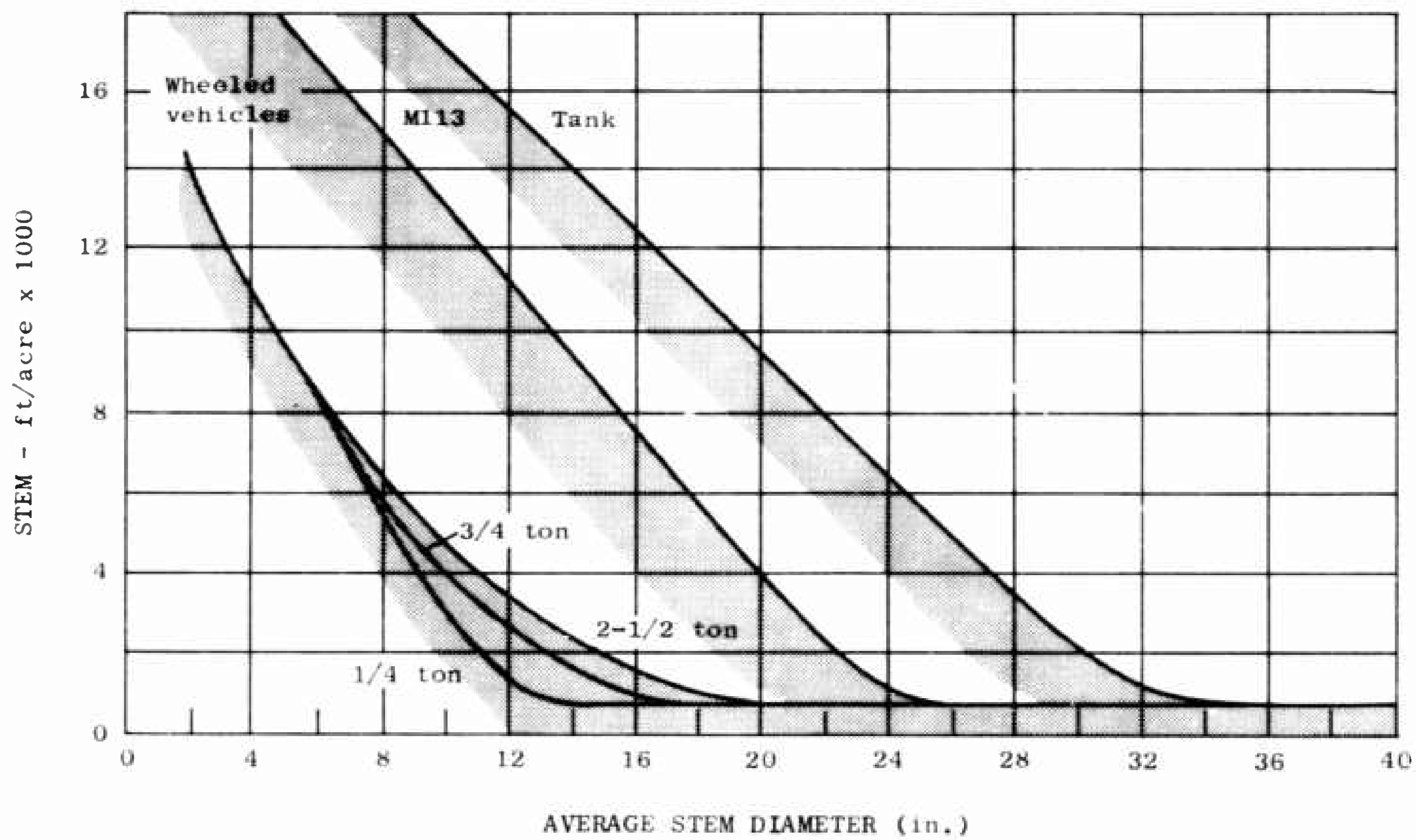

Fig. 15-10. Debris Characteristics Preventing Circumferential Movement of Vehicles

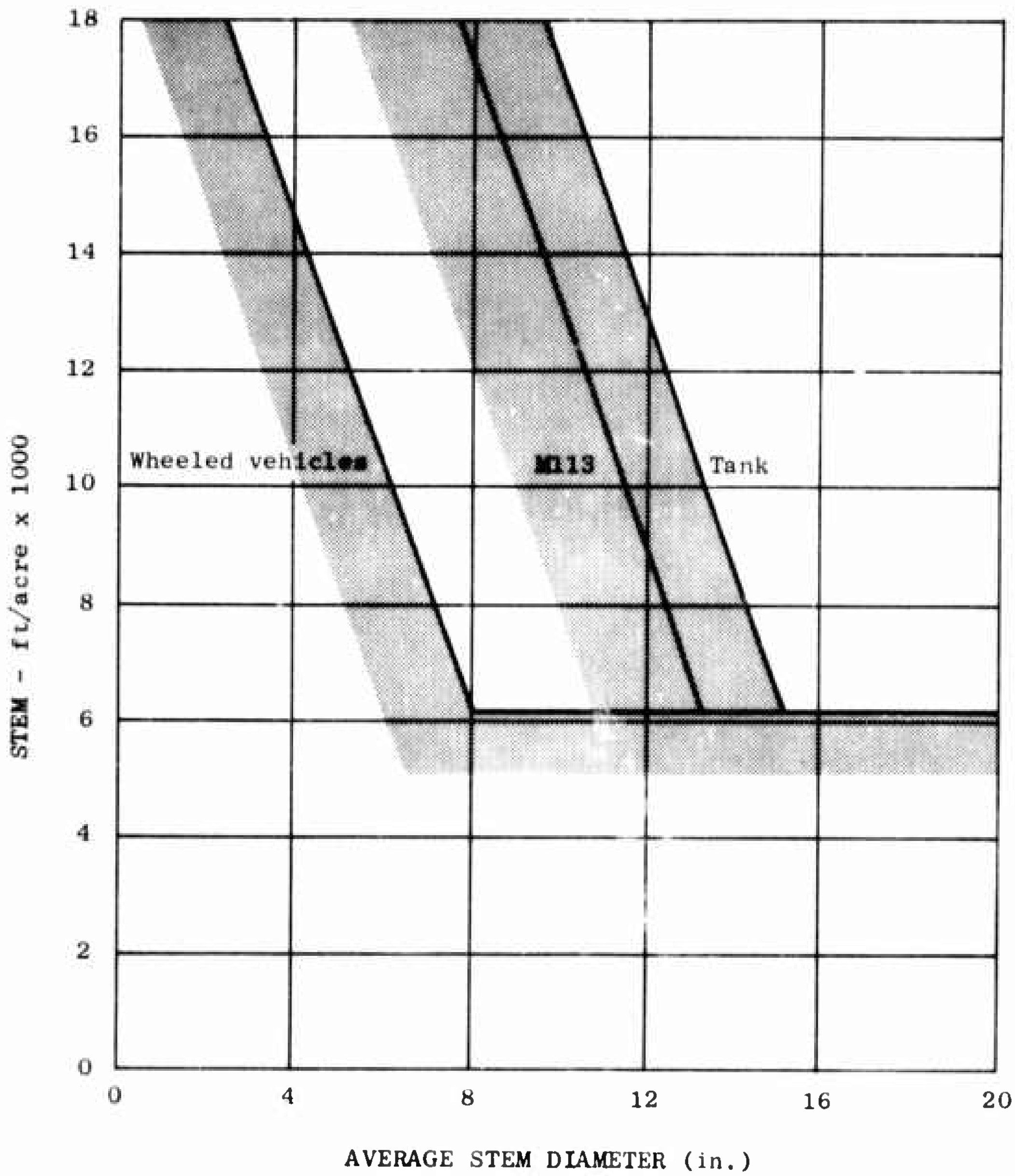

Fig. 15-11. Debris Characteristics Preventing Radial Movement of Vehicles

the debris zones in which they were tested. It should also be noted that tracked vehicles could climb onto the debris and mat it down after a number of passes, with the result that wheeled vehicles might pass, although this was not tested.

15.1.5 <u>Troop Movement.</u> The movement of troops through blowdown debris is an extremely difficult factor to present quantitatively. Many factors other than the physical obstacle itself have considerable effect. Such factors as visibility, leadership, size of force, mission, and what the troops are carrying are also influenced by the debris and indirectly affect movement. Movement of troops through a debris zone can be compared with moving through a thick jungle, although radial movement is generally easier than circumferential. Branch debris in a broadleaf forest blowdown area adds difficulties, particularly in visibility, which are not as severe in coniferous forest debris. Troop trials were conducted on both TNT detonations previously described; a summary of the results follows.

The troop tests conducted in conjunction with the rain forest detonation involved comparisons between preshot and postshot tests of day and night patrols and platoon exercises with a mortar squad and tests with stretcher parties. All movement was along radial directions from GZ. In addition, radial and circumferential movement of individuals was measured. The results of the individual movement tests are shown in Table 15-3. The differences between moving toward GZ and away from GZ are due to the test requirement that individuals maintain a compass bearing toward or away from GZ. Going toward GZ, the objective could be seen at a ground range of 985 ft (300 m), and compass checks were no longer necessary. Thus visibility had a large effect on movement rates. Table 15-3 indicates only a small difference between radial and circumferential movement. What the data do not show is the considerably greater effort required to move circumferentially. Greater differences would have been observed if the trials had been conducted over greater distances. The general conclusion from objective and subjective observations is that, except for the 800- to 1070-ft (245- to 325-m) ground ranges, movement on foot proved easier than in the virgin jungle.

Table 15.3

COMPARISON OF RADIAL AND CIRCUMFERENTIAL MOVEMENT RATES FOR TROOPS IN A RAIN FOREST BLOWDOWN AREA, 1-KT NUCLEAR

Ground Range	Debris Type	Average Movement Rates ft/min (m/min)					
		Radially Towards GZ	% Diff	Radially Away From GZ	% Diff	Circumferentially	% Diff
540 ft (165 m)	log	184 (56.1)	+71	130 (39.3)	+40	150 (45.4)	+51
800 ft (245 m)	log w/ branch	150 (45.7)	+39	100 (30.8)	+10	116 (35.4)	+18
1030 ft (314 m)	dense branch	88 (26.8)	-19	67 (20.4)	-27	75 (22.9)	-24
Virgin jungle		108 (32.9)		42 (28)		100 (30)	

The night and day patrols were conducted over an approximately 2130-ft (650-m) route, with one leg from virgin forest to the vicinity of GZ, then back to the virgin forest on a different bearing. No essential difference in elapsed time before and after detonation for the patrols was observed. The "branch with log" and "dense branch" regions (ground ranges 805 to 1066 ft) presented the most serious obstacles; footholds were insecure, there was constant danger of falling, and movement was physically exhausting. However, thinning and removal of the forest canopy with consequent increase in visibility permitted easier navigation and control, more open patrol formation, and more rapid movement overall compared to the virgin forest, particularly in the other damage zones. In addition, removal of vines and branches and the layer of leaves resulting from the explosion allowed more silent movement.

In the platoon attack trails, control problems were considerably eased in the blowdown area compared to the virgin forest, owing to increased visibility. Platoon objectives were in the vicinity of GZ, such that the loss of cover between GZ and 656 ft (200 m) ground range placed the attacking platoon under enemy observation at a time when it was trying to surmount the debris obstacles. Except for the mortar squad, the platoon arrived at the objective in good condition. It was apparent that the load carried and its awkwardness, together with the difficulties imposed in surmounting obstacles, contributed to the more rapid exhaustion of the mortar squad.

Tests with a loaded two-man stretcher indicated that carriage through blowdown debris was very difficult. The stretcher bearers' attention was diverted from the patient because of the need to concentrate on finding suitable footing. Consequently, the casualty had a very rough trip and was frequently struck by debris. The conclusion drawn from this trial was that the probability for survival of a casualty with a severe wound would be significantly reduced. If the casualty survived the carriage, it is almost certain that he would experience a marked degree of secondary shock.

Troop trials conducted in the coniferous forest blowdown consisted of radial and circumferential platoon exercixes, including a mortar squad, and a simulated casualty-moving test. Some movement rate data were obtained and are presented in Table 15-4. Movement in the preshot forest was comparatively easy; movement in the blowdown was far more difficult. This contrasts with the data shown in Table 15-3 for rain forest blowdown. The data in Table 15-4 were obtained from platoon exercises in which troops advanced at "ordinary" or "best possible" speed as a skirmish line, followed by a mortar squad. Radial movement time data were not obtained, because the rapidly changing character of the debris made it difficult to correlate movement rate with debris characteristics. In circumferential movement over a 820-ft (250-m) distance, it generally took twice as long for the platoon moving in the debris zone as in the preshot forest. The mortar squad had considerably more difficulty because of the weight and awkwardness of the equipment. It was concluded that in a larger, more realistic distance, the 2-to-1 time ratio would be greater, with the mortar squad becoming extremely fatigued. Another trial was conducted, as above, in which the troops wore gas masks. The time to traverse the route was further increased and the men were completely winded and in no condition to assault an enemy position.

Evidently the obstacle effectiveness of the debris could be greatly enhanced by employing mines and booby traps.

Table 15-4

COMPARISON OF CIRCUMFERENTIAL MOVEMENT RATES FOR TROOPS IN A CONIFEROUS FOREST BLOWDOWN AREA, 1-KT NUCLEAR

Ground Range	Debris Type	Circumferential Movement Rates ft/min (m/min)			
		Ordinary Advance	% Diff	Best Possible Speed	% Diff
705 ft (215 m)	Bare stem	268.3 (81.8)	-13	468.7 (142.9)	-29
1115 ft (340 m)	Stem with branches attached	157.8 (48.1)	-49	213.5 (65.1)	-68
	Preshot forest	307.3 (93.7)		659 (200.9)	

Skirmish line movements in the radial direction indicated little increase in total traversing time. Although there was slowing in some zones, movement was easier at less than 980 ft (300 m). The mortar squad again had the greatest difficulty. Since troops would tend to follow the line of least resistance, i.e., between tree stems, the platoon tended to converge as it traveled toward GZ.

An administrative march was also conducted over a radial-circumferential-radial route. The circumferential portion was in the area of maximum blowdown debris. Movement was very slow; in one instance the mortar squad could not keep up with the infantrymen and lost contact.

A platoon night attack similar to the first circumferential trial described but in the opposite direction was performed. The platoon was organized as three attacking squad columns in line, except for the last 295 ft (90 m) where they deployed as a skirmish line. The 2-to-1 ratio in time again was observed.

The moving of a simulated casualty by two- and four-man stretcher bearer teams traveling circumferentially was also conducted. Results were essentially the same as those from the rain forest trials. Apparently, some form of removing serious casualties other than carrying through the debris zone may have to be employed.

It is hoped that the preceding discussion of tests and results concerned with troop movements is sufficient for the reader to develop an understanding of conditions and expectations for operations in a forest blowdown area. Since there are few quantitative data, we must, to a large extent, rely on subjective evaluation. However, since these evaluations were performed mainly by qualified military personnel, considerable reliance can be placed on their findings.

15.1.6 <u>Predicting Effects on Movement.</u> The technique for determining the effects of forest debris on movement and the ground range at which they occur depend on the utilization of Figs. 15-1 through 15-7, and Figs. 15-10 and 15-11. The following examples will illustrate these techniques:

Example 15-3

Given: A conifer forest with an average diameter at breast height, d_{bh}, equal 13.5 in. and an average density of 140 trees per acre.

Find: Does this forest have the potential of hindering the movement of vehicles.

Solution: The greatest obstacle to vehicle movement will occur at the severe damage level corresponding to 90 percent trees down. The debris characteristics at this damage level are:

$$\text{stem-ft/acre} = \text{forest density} \times \text{average forest height} \times \text{percentage down}$$

$$= 140(80)(0.9)$$

$$= 10,000 \text{ stem-ft/acre}$$

from Eq. (15.1)

$$d_a = \frac{5d_{bh}}{7 - \frac{18}{H}}$$

$$= \frac{5(13.5)}{7 - \frac{18}{80}}$$

$$= 10 \text{ in.}$$

From Fig. 15-10 for circumferential movement, the point corresponding to a debris density of 10,000 stem-ft/acre and a debris diameter of 10 in. falls above the line for wheeled vehicles indicating no movement is possible, and is just in the "difficult" zone of M113 type tracked vehicles indicating minor difficulties. The same results occur for radial movement from Fig. 15-11.

This example illustrates that it is possible with a minimum of information to determine the potential effect on movement of a particular forest if damaged by nuclear airblast.

Example 15-4

Given: The forest of Example 15-3 with good site conditions and Class I trees. A surface burst of 200 KT is to be used.

Find: What are the ground ranges to light, moderate, and severe damage.

Solution: From Fig. 15-4 the overpressures for the damage levels are

Light = 1.6 psi

Moderate = 2.2 psi

Severe = 2.7 psi

From Chapter 2 HOB charts, the scaled ground ranges can be found. The actual ground ranges are

$$\text{Light} = 3050(200)^{1/3} = 17{,}840 \text{ ft}$$

$$\text{Moderate} = 2500(200)^{1/3} = 14{,}620 \text{ ft}$$

$$\text{Severe} = 2250(200)^{1/3} = 13{,}160 \text{ ft}$$

From this example, it is learned that wheeled vehicles will be stopped at a ground range of 13,160 ft. However, it is at times advantageous to know something of the extent of the zone where the wheeled vehicles would not operate. The technique for accomplishing this is illustrated in the following example.

Example 15-5

Given: The forest and burst conditions of Example 15-4. Severe damage at 13,160 ft, Moderate damage at 14,620 ft, and Light damage at 17,840 ft.

Find: What are the limits of the zones of effects on vehicle movement.

Solution: It was found in Example 15-3 that when the debris characteristics were plotted on Figs. 15-10 and 15-11, the point just fell within the boundary of the "difficult" zone for M113 type tracked vehicles so that a minor hindrance is all that is expected. Therefore, it can be concluded that the zone of this effect would be quite limited and will no longer be considered.

A vertical line is drawn from the plotted point downward till it intersects the zone boundaries (see Figs. 15-12 and 15-13). Using the 1/4-ton truck curve of Fig. 15-12, it is determined that the lower limit for preventing circumferential movement is 3000 stem-ft/acre. The limits for the "difficult" zone are 2,000 and 3,000 stem-ft/acre. These correspond to 20 and 30 percent down for the forest in question. Through simple interpolation, the ground ranges for these zones can be found. The general equation is

$$\frac{R_x - R_{50}}{50 - x} = \frac{R_{10} - R_{50}}{50 - 10}$$

where R_x, R_{10}, and R_{50} are the unknown ground range, ground range to 50 percent down (Moderate damage), and ground range to 10 percent down (Light damage). The ground range to 30 percent down is 16,230 ft and the ground range to 20 percent down is 17,040 ft. The extent of the no movement zone is therefore from 13,160 ft to 16,230 ft, and the extent of the "difficult" zone is from 16,230 ft to 17,040 ft for circumferential movement. A like procedure for radial movement indicates a no movement zone from 13,160 ft to 14,180 ft, and a "difficult" zone from 14,180 ft to 14,550 ft.

This example illustrates that it is possible to obtain an estimate of the extent of the zones for difficult and no movement. However, this estimate is limited to ground ranges between 20-90 percent trees down. If in the previous example, the limit of the difficult zone for circumferential movement had been 1,000 stem-ft/acre or 10 percent trees down, the 20 percent value should be used. The debris at ground ranges less than the 90 percent down range also effect movement. In fact, there should be a "difficult" zone between the severe damage and destroyed ground ranges.

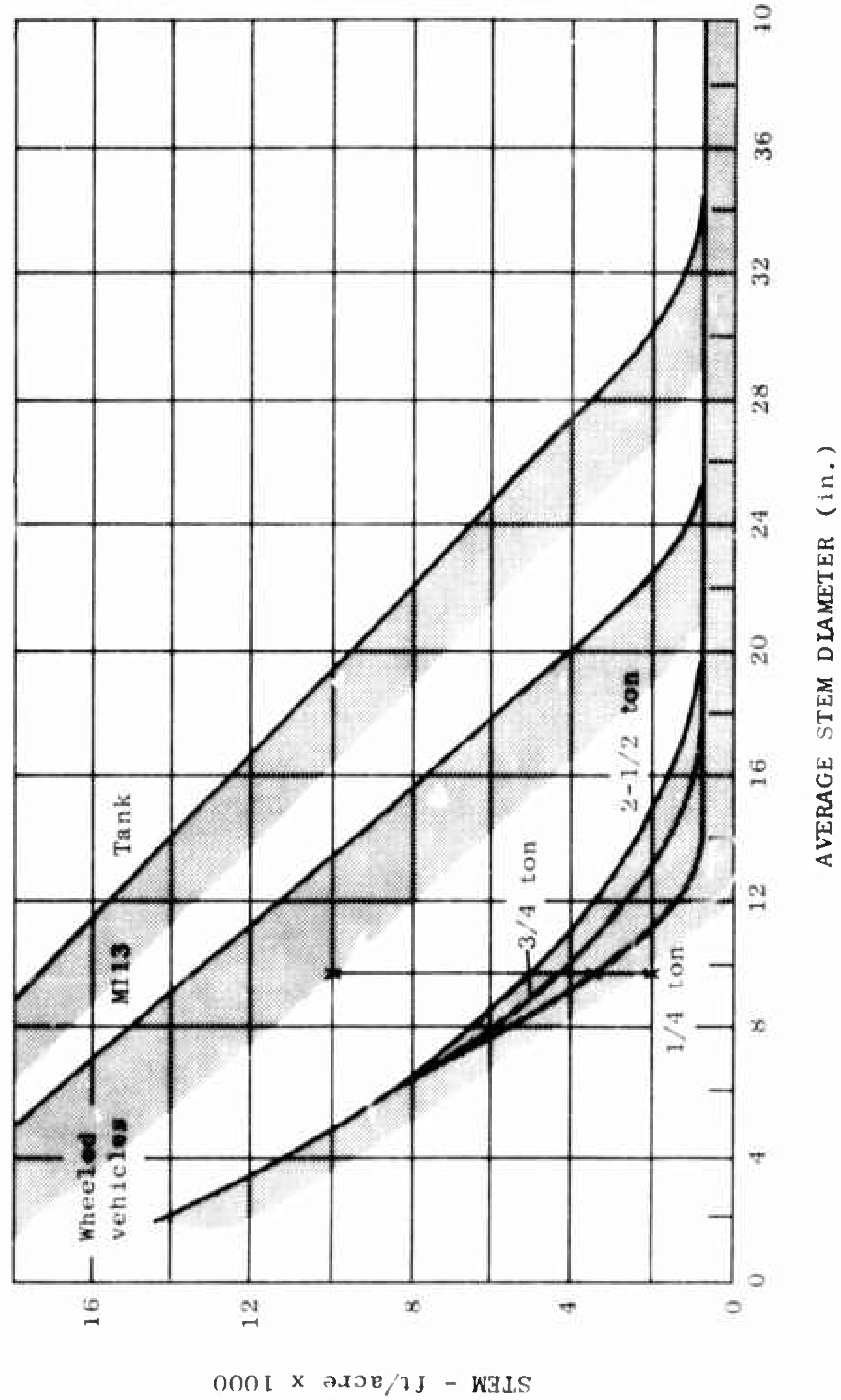

Fig. 15-12. Debris Characteristics Preventing Circumferential Movement of Vehicles

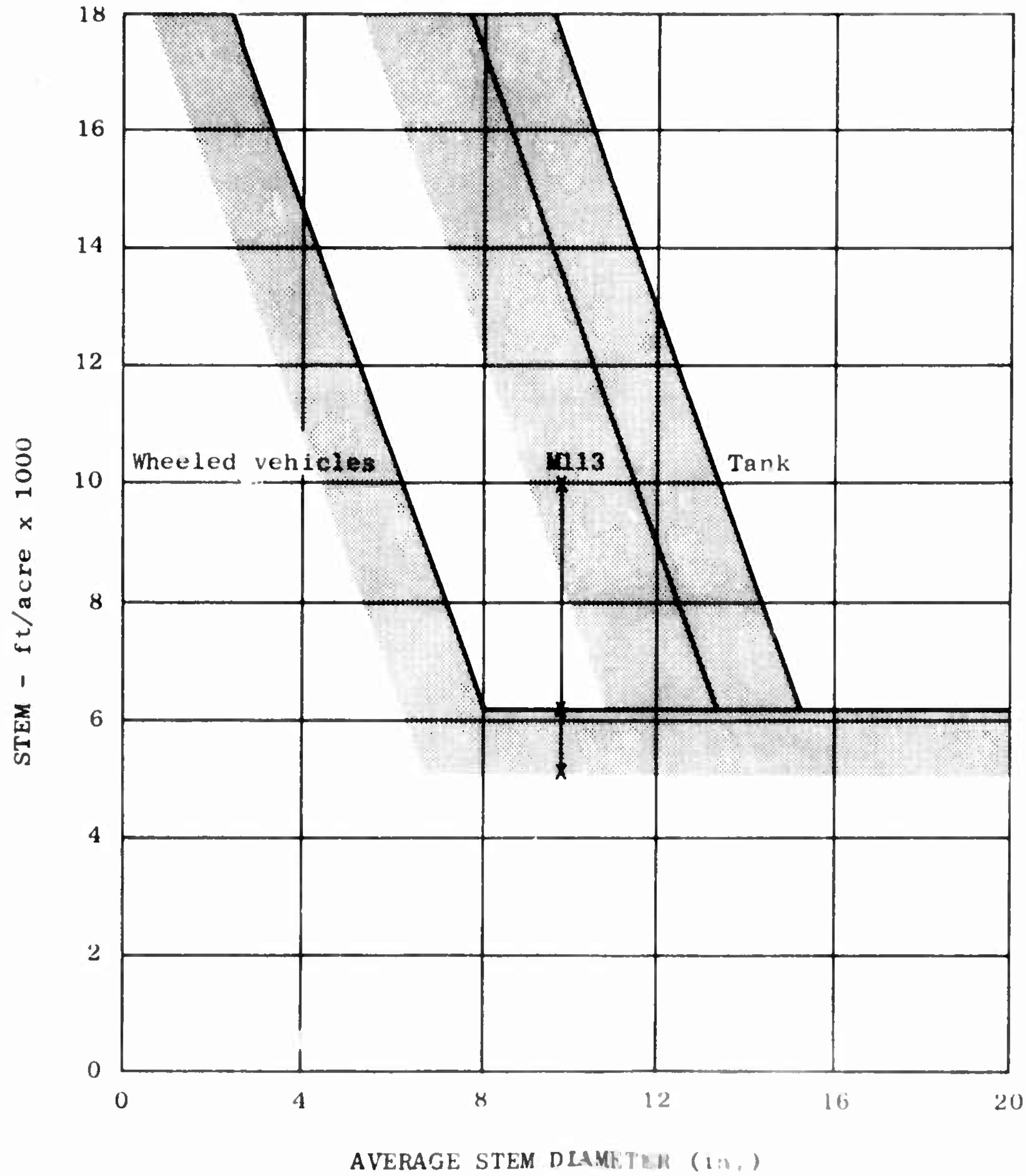

Fig. 15-13. Debris Characteristics Preventing Radial Movement of Vehicles

However, the location of this zone is difficult to pinpoint given the limited information available. The nature of the debris between the severe and destroyed ground ranges changes very rapidly, and consequently its effect on movement.

15.1.7 Debris Clearance. Previous sections have discussed the nature of the forest debris and its effect on the movement of troops and vehicles. If a hindrance to movement is created, the question arises as to whether to clear a route through the debris or to bypass it if possible. A prediction technique to quantitatively evaluate debris clearance rates for a specific situation is not available. However, information from Ref. 9 pertaining to data obtained on Operation BLOWDOWN and Operation DISTANT PLAIN can be of value in evaluating route clearance as an alternative.

Two basic techniques of debris clearance have been tested for both opening a new route and reopening an existing preshot route. These are clearance by hand methods or by machine. The debris clearance tests involved opening a 12-ft wide route suitable for passage of wheeled vehilcles.

A TD18A tractor equipped with an angle dozer blade and winch was used in the rain forest debris clearance tests. Reopening of routes or construction of new routes always proceeded faster than opening new routes in the virgin forest. This was because of improved visibility and less driver obstruction from falling vines and foliage. Reopening a preshot route proceeded at a faster rate than constructing a new route, and the slowest rates occurred in the severe damage zone. The average rate in the virgin rain forest was 713 ft per hour. The rates for reopening a preshot existing route varied from a low of 1080 ft/hr to 4800 ft/hr, and for constructing a new route through debris, the variation was from a low of 1080 ft/hr to 1360 ft/hr.

A D7 tractor equipped with an angle dozer blade was used in clearing debris in the coniferous forest. Results were influenced by weather. Rain affected the soil so that most of the time the tractor operated at belly-pan depth and the resulting ruts would not allow passage of wheeled vehicles.

The same general results as obtained in the rain forest were obtained in the coniferous forest in that clearance rates were faster than in the virgin forest.

Trials were also conducted in the coniferous forest with a rubber tired front end loader with a 2-1/2 cubic yd 4-in-1 bucket. Tests were not very successful because of soil conditions mentioned previously. The front end loader generally became hopelessly mired. The general conclusion was that this item of equipment could be very effective in clearing debris.

Different methods were evaluated for hand clearance of debris. The rain forest trials were conducted with an engineer section of 1 NCO and 8 men organized and operating as follows:

1. Clearance Party. This party was composed of 2 men (each equipped with a machete), whose task was to clear small debris so that the following heavier equipment parties had immediate access to the cutting points.

2. Axe Party. This party of 2 men, each with an axe and machete, cut felled trees less than 6 in. in diameter. This party concentrated on those trees laying in contact with the ground.

3. Chainsaw Party. A party of 2 men, one equipped with a 15-in. chainsaw and a machete, the other equipped with an axe and a machete, cut all blowdown left by the preceding parties, i.e., logs over 6 in. in diameter and smaller logs and branches above the ground.

4. Debris Removal Party. This party removed debris from the roadway by moving it to the most convenient side. The 2 men in this group had one crosscut saw and each man was equipped with a machete.

5. Control Party. The NCO, equipped with a machete, controlled the operation and provided assistance when required by any other party.

The clearance rate through virgin rain forest was 73 ft/hr. The clearance rate for constructing a new route varied from 41 ft/hr in the severe damage zone to 73 ft/hr in the light damage zone. When clearing a preshot route, rates varied from 59 ft/hr in the severe damage zone to 340 ft/hr in the light damage zone.

The coniferous forest trials were conducted using the following organizations and methods based on an engineer section of 9 men and 1 NCO.

Method I

Method I had a section of engineers equipped with two 2-man crosscut saws and 3 single-edged axes. The squad was divided into three parties, a notching party of 3 men with axes, a saw party of 4 men with the two crosscut saws and a 2 man debris party. The NCO provided general supervision of the work force.

The notching party, under the direction of the NCO, moved ahead of the other parties and notched the trees to be felled. In order to minimize secondary cutting or moving, the trees were notched so that when cut they fell out of the clearance route.

The saw party next felled the notched trees. The debris party aided this operation in providing pressure to the tree stem to ensure that it fell in the notched direction.

The debris party completed tree removal by lifting the stem and twisting it off the route. In some cases, the saw party made a secondary cut on a felled tree of the length required to clear the route and only this section was removed.

After the notching party had notched the trees in the designated area, they joined the debris party and worked with them until the sawyers started felling the last tree. At this time the notchers were required to leave the work party; this exercise simulated the effect of continuing the clearance over a longer path where the notchers would be required to resume notching trees.

Method II

Method II was executed in the same manner as Method I with the exception that a 1 man, 18- or 24-in. gasoline-powered chainsaw replaced one of the 2-man crosscut saws. The released man joined the debris party.

Method III

Method III was similar to Methods I and II; however, both crosscut saws were replaced by gasoline-powered chainsaws. This method demonstrated the greatly enhanced clearance ability provided by the second chainsaw.

Method IV

This procedure combined the use of the gasoline-powered chainsaw and explosives to clearing the required route. Three axes, one gasoline-powered chainsaw and half-pound sticks of C4 explosive (with necessary emplacement and detonating equipment) were used.

A simultaneous approach was used with this method. The NCO surveyed the route with a demolition expert to decide which trees would be removed by explosives and which would be felled by chainsaw. The notchers then notched those trees which were to be felled by chainsaw in a manner similar to Method I while the two demolition experts were emplacing charges under the root structure of the trees to be removed by explosive. The chainsaw party felled only notched trees. The debris party followed, operating as in Method I. The demolition experts planned to finish at the same time as the chainsaw felling party. In one instance the chainsaw party moved faster and was directed to continue felling those trees which had originally been designated for explosive removal until such time as the explosive party was ready to detonate. When the demolition charges were in place, the troops in the area were cleared to a safe distance and a 70-second safety fuse lit. After detonation the section party re-entered the area and removed by chainsaw, axe, and hand, any stems which were hung up or not removed by the explosion.

The following table summarizes the results of these trials. In all cases, the minimum clearance rates postshot occurred in the severe damage zone. As can be seen,

Table 15-5

RESULTS OF HAND CLEARANCE TRIALS IN A CONIFEROUS FOREST, ft/hr

Method	Average Rate Virgin Forest	Minimum Rate Reopen Route	Minimum Rate New Route
I	380	260	126
II	543	425	212
III	1,550	554	292
IV	388	No Data	159

Methods II and III gave the best results. These data on the techniques of hand clearing debris are presented only as a guide and an aid to assist the reader in becoming familiar with debris clearance, as was the data on clearance by machines. Comparisons between the two test forests, and application of quantitative results to other forests should be done with extreme caution. In addition to the obvious differences between the two forests (broadleaf vs conifer, and underbrush vs no underbrush), the differences in the amount and nature of the debris; one additional difference should be noted along with its implications.

As noted previously, the site conditions for the coniferous forest were poor. As a consequence, 85 percent of the trees failed through uprooting. In contrast, good site conditions prevailed for the rain forest and only 50 percent failed by uprooting. As a consequence, debris clearance in the coniferous forest was relatively more difficult because there were a greater number of root balls to be removed. This will be particularly true if just hand clearing methods are used.*

Poor site conditions may also pose trafficability difficulties for certain types of equipment. This occurred, as mentioned previously, on Operation DISTANT PLAIN where the poorly drained silty soil could not support the rubber tired front end loader or the D7 tractor adequately after a rain. The D7 was able to clear the route of debris, but additional effort would have been required to make the route passable to wheeled vehicles because of ruts left by the tractor. The rubber tired front end loader became mired and was of no use.

15.1.8 Road Obstacles. A concern which merits specific attention is what is the effect of forest blowdown on roads in the forest. This depends a great deal on the orientation of the road with respect to GZ. The two orientations discussed represent extremes and are roads oriented radially from GZ and roads oriented perpendicular to a radial from GZ or chord roads. The latter represent roads which intersect the circular zones of forest damage.

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* It was found that if a 4 to 8 ft section of tree stem was attached to the root ball, it could be used as a lever to move the root ball.

Radial roads are difficult to block with forest blowdown debris because felled trees generally have a radial orientation also. Therefore, it is by chance that a tree alongside a roadway would fall into the roadway instead of alongside it. Trees generally fall within a $\pm 10^{\circ}$ of a radial orientation. This divergence may be greater for forests of high tree density. Using $\pm 10^{\circ}$ as a limit, it is possible to determine that the distance between tree lines on either side of the roadway would have to be equal to or less than 30 percent of the average height of the forest in order to have a significant number of trees to fall onto the roadway. However, this is not expected to cause much difficulty or hindrance to the movement of troops or vehicles along the road. Any difficulties are expected to be larger in a broadleaf forest than in a coniferous forest because of greater amounts of branch debris. Even if the roadway were in a cut which would promote fallen trees sliding or rolling down onto the roadway, no major difficulties are anticipated and minimal clearance of debris would be all that would be required.

Chord roads present quite a different problem in that the effect of trees falling across the road must be evaluated. The primary effect of the roadway is to decrease the debris density. If the roadway and right of way are wider than the height of the trees along its edge, a clear zone would exist on the side of the right of way furthest from GZ, permitting a bypass of the obstacle. As a rule of thumb, if the average forest height, H, is less than 1.2 times the distance between the tree lines on either side of the right of way, W, then minimal obstacles, if any, would be formed. In those cases where the forest height is sufficient, then the effects on movement must be evaluated with the debris density expected on the roadway. The debris density on the roadway can be found from the following expression.

$$S_r = \frac{S_f}{1 + \frac{1.2W}{H}} \qquad (15.3)$$

where S_r is the debris density in stem-ft/acre on the roadway, S_f is the stem-ft/acre in the forest, and H and W have been previously defined. In addition, the average diameter of the debris, d_a, must be reduced by 25 percent. An example will serve to illustrate the technique.

Example 15-6 (C)

Given: The forest debris and burst conditions of Examples 15-4 and 15-5. A 50 ft right of way with a two lane road passes within 14,600 ft of ground zero corresponding to the Moderate damage range (50 percent down).

Find: Is movement of wheeled vehicles restricted? If so, to what extent.

Solution: The debris density in the forest is

$$= 0.5(80)(140)$$

$$= 5,600 \text{ stem ft/acre}$$

The debris density on the roadway is found from Eq. (15.3).

$$S_r = \frac{5600}{1 + \frac{1.2(50)}{80}}$$

$$= \frac{5600}{1.75}$$

$$= 3200 \text{ stem-ft/acre}$$

The average diameter of the roadway debris is

$$d_r = 0.75 \text{ da}$$

$$= 0.75 \ (10)$$

$$= 7.5 \text{ in.}$$

From Fig. 15-10, it is determined that the road will be passable to wheeled vehicles but with considerable difficulty.

15.1.9 Limitations and Accuracy. The mathematical model upon which the prediction technique for determining ground range to the damage zones is based on two assumptions. These are that trees are loaded by a single shock with a velocity perpendicular to the axis of the tree, i.e., Mach region shocks, and that the thermal pulse does not alter the load transferred to the tree.

The former assumption is of concern where the forest or a part of the forest is located in the regular reflection region. In this case, the trees are loaded by two or more shocks moving with a velocity other than perpendicular to the tree stem. An extreme example would be a tree located directly under an air burst where the velocities of the incident and reflected shocks are parallel to the stem. For incident overpressures on the order of 20 psi or less, the result is likely to be bare standing tree stems with stripped branches littering the forest floor. Therefore, under certain burst conditions, it is possible there could be a zone of bare stems at ground ranges less than where virtually complete removal of vegetation has occurred. As long as the ground ranges to the various damage zones are determined from overpressures in or very nearly in the Mach reflection region, no difficulty should be encountered.

Thermal radiation may have two possible effects on the extent of forest blowdown. The force in the blast wave is transferred to the tree through aerodynamic forces on the foliage and to some extent on the branches. Thermal radiation from high yield bursts on the order of 50 to 100 KT or more may cause some defoliation which reduces the tree crown drag which in turn reduces the forces acting on the tree stem. If this in fact does occur, then the prediction technique of Section 15.1.2 would overestimate the ground range to a particular damage zone. A limiting condition can be determined for broadleaf trees using Fig. 15-3 for defoliated broadleafs. Data are not available to establish this limit for conifer forests.

The other effect of thermal radiation may be the alteration of blast forces by precursor phenomena. The same processes which could cause some degree of defoliation may liberate sufficient smoke and steam to trigger a precursor through the forest canopy. As overpressure levels are usually depressed and dynamic pressure impulses increased compared to non-precursor shock waves, the prediction technique could underestimate the ground ranges to damage zones. Thus the overall effects of thermal phenomena may be self-compensating to some degree. Unfortunately, there has been no investigation of these possible thermal effects, thus reduced accuracy for yields greater than 100 KT must be assumed.

Another area where insufficient information exists is the possibility of debris translation and pile-up by the blast winds. This is often referred to as the "snow fencing" mechanism where translated debris would be piled up against still standing trees in the light to severe damage zones, thereby increasing the obstacle effectiveness. The translated debris predominately originates from what has been described as the destroyed area. Debris from the area is highly fragmented with some of it being consumed in the fireball or transported with the turbulent winds associated with fireball rise. The remainder is transported by the high velocity air flow associated with the air blast wave. The size and mass distribution of this debris is such, and it is spread over a wide enough area, that is has not been observed to constitute a significant part of the debris obstacle. Little or no evidence of "snow fencing" was observed on either of the two HE trials previously discussed. However, the yields of these two trials was so low that the blast winds were of very short duration, therefore minimizing this effect if it does occur. Large yield data (100 KT and 15 MT) showed no evidence of "snow fencing"; however, this data is inconclusive because of the limited nature of the forest stands (see Ref. 11). This issue cannot be resolved with present data, and the only statement that can be made is that a further uncertainty must be acknowledged in predicting effects on movement for yields greater than 100 KT.

The computer model upon which this prediction technique is based employs an empirical relationship giving dynamic pressure impulse as a function of overpressure and yield. This relationship was derived from studies with deterministic computer codes of ideal blast wave generation and propagation phenomena. As there are evident differences between ideal and actual conditions and data, a degree of uncertainty exists which as yet has not been quantified.

Discussions of accuracy and reliability are, to some extent, contained in each of the previous sections. In summary, considerable confidence can be placed in the accuracy of the prediction technique for determining ground range to particular damage zones. Expected accuracy is ±15 percent. The accuracy in predicting the effects on vehicle movement is not as good; however, within the context of the broad categorization of effects on movement, overall accuracy is still expected to be ±15 percent. Some degradation in accuracy must be assumed for yields greater than 100 KT.